PSYCHOLOGICAL REVIEW PUBLICATIONS FEBRUARY, 1917

Journal of Experimental Psychology

EDITED BY

JOHN B. WATSON, JOHNS HOPKINS UNIVERSITY
HOWARD C. WARREN, PRINCETON UNIVERSITY (*Editor*)
JAMES R. ANGELL, UNIVERSITY OF CHICAGO (*Monographs*)
EDWARD B. TITCHENER, CORNELL UNIVERSITY (*Psychological Review*)
WALTER S. HUNTER, CLARK UNIVERSITY (*Bulletin*) AND
MADISON BENTLEY, UNIVERSITY OF ILLINOIS (*Index*)

ADVISORY EDITORS

CHICAGO: RAYMOND DODGE, WESLEYAN UNIVERSITY; KNIGHT DUNLAP, JOHNS HOPKINS UNIVERSITY; H. S. LANGFELD, HARVARD UNIVERSITY; E. L. THORNDIKE, COLUMBIA UNIVERSITY.

CONTENTS

Visual Stimulation Intensities: LEONARD T. TROLAND. . . . 1

A New Method for Reaction Time: F. E. AUSTIN. . . . 32

Visual Discrimination of Areas Illuminated by Varying Degrees of Intensity: F. E. AUSTIN. . . . 37

Memory for Pictures: A Preliminary Study: HAROLD E. BURTT. . . . 63

A Comparison of Visual and Auditory Memory in Children: [illegible] . . . 76

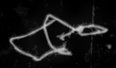
Reviews: KNIGHT DUNLAP. . . . 83

PUBLISHED BY THE

PSYCHOLOGICAL REVIEW COMPANY

PRINCETON, N. J.

Entered as second-class matter at Post-Office at Princeton, N. J.



CONTENTS OF VOLUME II

February.

On the Measurement of Visual Sensation Intensities. LEONARD T. TROLAND, 1.
A New Method for Measuring Reaction Time. F. E. AUSTIN, 34.
Visual Discrimination of Rectangular Areas Illuminated by Varying Degrees of Achromatic Light. G. F. ARPS, 41.
Auditory Illusions of Movement—A Preliminary Study. HAROLD E. BURTT, 63.
A Comparison of Deaf and Hearing Children in Visual Memory for Digits. RUDOLF PINTNER and DONALD G. PATERSON, 76.
A New Complication Apparatus. KNIGHT DUNLAP, 89.
Discussion. H. B. REED, 92.

April.

Some Tests on the Memorizing of Musical Themes. KATE GORDON, 93.
Quantitative Tonal Stimuli without Qualitative Change. HAROLD A. RICHMOND, 100.
The Focal Variator. A. P. WEISS, 106.
Hipp Chronoscope without Springs. H. C. WARREN and PRENTICE REEVES, 114.
Systolic Blood Pressure Symptoms of Deception. WILLIAM M. MARSTON, 117.

June.

The Effect of Rapid Changes of Work on the Rate of Performance. J. CROSBY CHAPMAN, 165.
Apparatus for Recording Continuous Discrimination Reactions. H. C. MCCOMAS, 171.
Experiments in Ball Tossing: The Significance of Learning Curves. JOSEPH PETERSON, 178.
The Speed and Accuracy of Motor Adjustments. JOHN J. B. MORGAN, 225.
The Johns Hopkins Chronoscope. KNIGHT DUNLAP, 249.

August.

A New Chronoscope and Fall Apparatus. PAUL E. KLOPSTEG, 253.
The Estimation of Distances by Sight and Passive Touch: Some Investigations into the Evolution of the Sense of Touch. ARTHUR B. FITT, 264.
Hand-Tongue Space Perception. C. N. WATERMAN, JR., 289.
Some Areas of Color Blindness of an Unusual Type in the Peripheral Retina. C. E. FERREE and GERTRUDE RAND, 295.
The Progressive Error of the Smedley Dynamometer. SAMUEL C. KOHS, 304.
Discussion:
The Tilting Board and Rotating Table. HENRY H. GODDARD, 313.

October.

A Repetition of Ebert and Meumann's Practice Experiment on Memory. H. B. REED, 315.
The Influence of Color on Apparent Weight. J. E. DECAMP, 347.
Tactual Illusions of Movement. HAROLD E. BURTT, 371.
Association-Reaction as a Test of Learning. KNIGHT DUNLAP, 386.

December.

Unidextrality and Mirror-Reading. JUNE E. DOWNEY and EDWIN B. PAYSON, 393.

The Differential Spatial Limen for Finger Span. HERBERT S. LANGFELD, 446.

A New Olfactometric Technique and Some Results. HERBERT WOODROW and BENJAMIN KARPMAN, 431.

The Memory Value of Mixed Sizes of Advertisements. HENRY F. ADAMS, 448.

Children's Sense of Harmonies in Colors and Tones. J. F. DASHIELL, 466.

The Relation between Learning and Retention and Amount to be Learned. V. A. C. HENMON, 476.

Journal of
Experimental Psychology

VOL. II, No. 1. FEBRUARY, 1917

ON THE MEASUREMENT OF VISUAL STIMULATION INTENSITIES

BY LEONARD T. TROLAND

Nela Research Laboratory, National Lamp Works of General Electric Company, Nela Park, Cleveland, O.

I. INTRODUCTION

It must probably be admitted that there are few fields of science in which definite quantitative results are obtainable, which have been more carelessly cultivated than that of visual psycho-physiology. The literature of visual research is truly monumental, the ascertained qualitative facts are legion, and yet the laws of vision are few and vague. The conditioning cause of our present chaotic conception of visual response is undoubtedly the failure of the majority of investigators in this realm to pay attention to details, chiefly, their failure to measure in absolute units the conditions and results of their experiments. As a consequence, the conditions are not reproducible, and the results can be employed in the support of almost any hypothesis, at the experimenter's pleasure.

The essentials for the standardization and accurate description of the work in vision have been available to intelligent students of the subject for a century, but only quite recently have these essentials been developed to a form in which they are readily applicable. There are now a number of workers on vision in this country whose methods can be described as exact and scientific. Much of this development—on the photometric side at least—has been the out, come of the technical demands of illuminating engineering-

and the debate over many methodological details is still far from arriving at a definite conclusion.

The conditions of stimulation for any experiment in monocular vision are unequivocally determined if the 'energy distribution curve' (*cf.* Fig. 1) is known for the total radia-

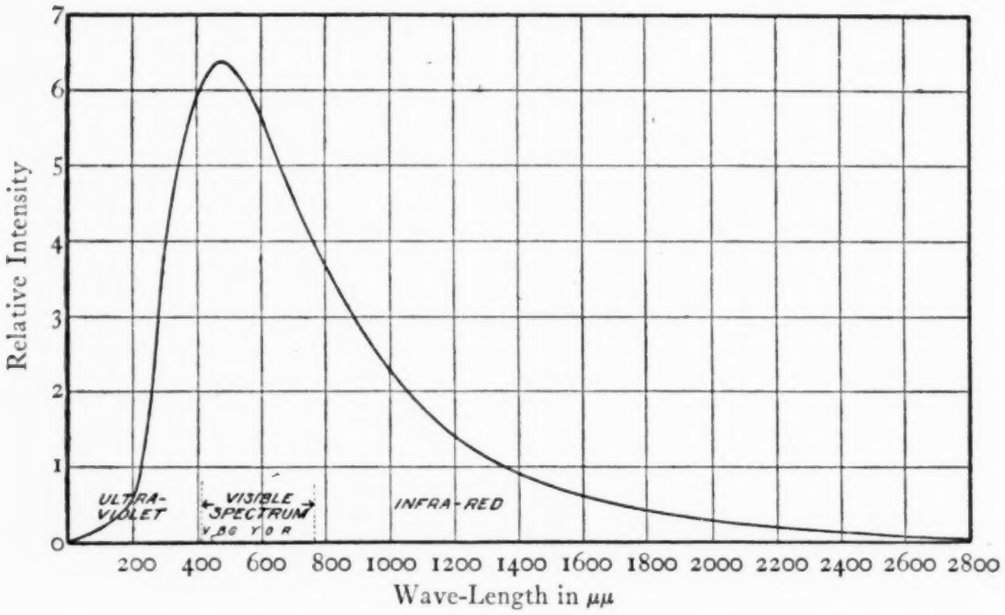


FIG. 1. Energy Distribution Curve of the Radiation from a "Black Body" at 6200° Absolute. The ordinates of this curve represent the 'specific radiant power density' for each wave-length, *i. e.*, they are proportional to the energy per unit wave-length, passing through a given surface in the path of the radiation, in a given time. The area enclosed between the curve and the axis of the abscissæ, is proportional to the 'total radiant power density.' (See note 1.) This distribution curve is closely similar to that of sunlight, and the sensation produced by such radiation would be approximately 'white.' It will be noticed that more than half of the energy lies outside of the visible spectrum. A thermopile will measure all of this energy, while a photometer can deal only with that lying in the visible spectrum.

tion falling upon each sensitive element of the retina. Since the visual receptors, proper, lie in the external strata of the retina, the state of affairs outside the eye is of importance only in so far as it determines that within the eye. The mode of this determination is not simple for any of the dimensions of the visual stimulus.

It is the purpose of the present article to give special consideration only to the general dimension of stimulation intensity. The discussion will be divided into three more or

less independent parts, the first dealing with the significance and usefulness of photometric as compared with radiometric measurements, the second considering the problem of the proper method for general photometry, and the third dealing with the influence of pupillary size upon visual stimulus intensity. The final object of the paper is the definition and justification of a standard unit of visual stimulus intensity, the *photon*. Little will be said which is essentially new, but in this field, at the present time, there is small danger that repetition will become over-emphasis.

II. Radiometry Versus Photometry in the Measurements of Stimulus Intensities

It no longer savors of originality to point out that the term 'intensity' has been employed in a very indefinite way by writers in psycho-physiological optics. It has been purposively so employed in the title of the present article. For a technical analysis of various possible meanings of the word, the reader is referred to a footnote,[1] which explains

[1] Rand (Psychol. Mongr., No. 62, 12) says: "This term [intensity] has been employed at various times to indicate (*a*) the energy of a beam of spectral light homogeneous as to color; (*b*) the white-value of a color; (*c*) the saturation of a color; and (*d*) the energy of light-waves reflected from a pigment surface as conditioned by the general illumination of the visual field." Further (p. 20) "The terminology which we propose to use . . . may be outlined as follows: *Intensity of stimulus* will be used to indicate the energy of light-waves coming to the eye. *Intensity of sensation*, or apparent intensity, will be used as its correlative subjective term. So used, it will signify merely energy or voluminousness of sensation and will have no reference whatever to the white-value of a color. . . . The terms *brightness* and *white-value* will be used interchangeably to indicate the lightness or darkness of a color."

Rand's system of intensity terms appears to be not less confused than that of previous workers. The fact is that practically every intensity term in vision has been employed at one time or another to denote the meanings of every other intensity term, so that any definite nomenclature must be more or less arbitrary. In the present paper the following classification will be utilized.

Intensity will be employed as a generic term to stand for any one of the group of allied dimensions which we are here discussing. The simplest method of defining these dimensions for the purposes of visual physiology is to consider them with direct reference to the retinal image.

From this point of view they are (1) the *total radiant power density*, or the number of ergs of radiant energy of all wave-lengths, striking the retina, per unit area, per unit time. This is the integral of the energy distribution curve for unit time and area, and is what would be measured by a surface thermopile (at the retina).

somewhat in detail the concepts to be used in the ensuing discussion.

One reason why the generalized visual stimulus is difficult to deal with lies in its extreme complexity. Physically speaking there is no such thing as 'homogeneous' light,[1] or a visual stimulus of a single wave-length. Homogeneity is a relative term only, since every light, no matter how 'pure,' must occupy a finite range of the spectrum, and hence must be constituted by an infinite number of wave-lengths, each

(2) *Specific radiant power density* or the number of ergs per unit wave-length of any single wave-length, striking the retina per unit area, per unit time. This is the value of the ordinate of the distribution curve for any given wave-length, or is the value of the derivative of the complete radiant power density with respect to the wave-length, for a given wave-length.

(3) *Retinal illumination*, or the luminous flux density at the retina, the number of *lumens* of *light* impinging upon the retina per unit area. This may be either *total* or *specific*, according as lights of all wave-lengths or of one wave-length, respectively, are considered. In the latter case the measure will be in lumens per unit wave-length.

(4) *Photometric brightness*, or the luminous intensity per unit projected area of any stimulus surface measured by the standard method of photometry, including only a surface of dimensions negligibly small in comparison with the distance to the observer. This, also, may be *total* or *specific* and, for a constant pupil, would be proportional to the retinal illumination, or *vice versa*. Photometric brightness is an external measure depending on the eye only for the relative values given to light of differing wave-lengths. It is measured in candles per unit area, or in lamberts.

(5) *Luminosity*, or apparent brightness; which is a wholly psychological variable, probably depending upon the degree of stimulation of the retina by given radiation. It cannot be expressed in any physical units, although equality of luminosities furnishes the basis for all photometric equations made by direct comparison. For a wide range of intensities, photometric brightness is independent of the absolute value of the retinal illumination, but the luminosity depends directly upon this quantity, and also upon the general state of sensitivity of the visual system.

(6) *Flicker value*, or the photometric brightness of any stimulus surface, as determined by the standard method of flicker photometry.

In order to avoid the introduction of odious technical terms into the text of the article, *total energy* will be employed as a synonym for 'total radiant power density,' and *specific (radiant) intensity* for 'specific radiant power density.' This amounts merely to a neglect of the fact that radiation has a definite energy density in space and is in motion.

A recent summary of photometric terminology is that of the 1915 Report of the Committee on Nomenclature and Standards of the Illuminating Engineering Society, *Trans. Illum. Eng. Soc.*, 1915, 10, 642–651. See also Rosa, E. B., 'Photometric Units and Nomenclature,' *Bull. Bur. of Stand.*, 1911, 6, 543–573.

[1] Exception might be taken to this statement on the basis of the modern 'quantum' theory of radiation, but such an exception is hardly relevant to the purposes of the present discussion.

with its own specific intensity. Only when the range is very short can we legitimately choose the average wave-length as representative of the whole range, and employ the total energy as the intensity measure. In all other cases we must either divide up the spectrum of the stimulus into a finite number of 'small ranges' of this sort, and state the total energy of each, or we must specify the function (or energy distribution curve) connecting specific (radiant) intensity with wave-length.

An important corollary of the above is that, physically, there is no such generic entity as 'white light,' a conception which is of so much importance in visual physiology. We might define white light physically as light, the energy distribution curve of which approximates that of solar radiation, or possibly that of the radiation from a so-called 'black body' at some definite temperature (see Fig. 1). However, the distribution curves of such types of radiation would be merely isolated examples, out of an infinite number of similar curves, having no essential peculiarities. A *uniform distribution* of energy over the visible spectrum would give rise to a sensation of (unsaturated) purple and not of white.

Another fertile cause of confusion in the discussion of the intensity relations of visual stimuli, is the double or compound meaning of the word 'light.'[1] Light, on the one hand, is a form of radiation, or moving electromagnetic energy, and on the other hand, is a quality of experience, or one dimension—at least—of visual sensation. According to current definitions, light-intensity—measured in lumens—is equal to radiant power—measured in watts—*multiplied by the relative luminosity producing capacity of the given radiation for the normal eye.*[2] This relative luminous capacity, 'stimulus coefficient,' or 'visibility,' is determined by a photometric equation of the given radiation to a standard, the radiant power of the standard being known or, at least, constant. Light, itself, is thus technically neither radiation nor visual

[1] *Cf.* Nutting, P. G., 'The Luminous Equivalent of Radiation,' *Bull. Bur. Stand.*, 5, 261–264, 1908. Also Cobb, P. W., 'Photometric Considerations Pertaining to Visual Stimuli,' *Psychol. Rev.*, 23, 72, 1916.

[2] *Cf.* Cobb, *loc. cit.*, pp. 87–88.

sensation but is a mathematical concept based upon both of these variables. When we speak of light we imply both radiation and sensation; but both radiation and visual luminosity can exist without any light existing. Light is measured by photometry, radiation by radiometry.

Any mass of radiation moving through space has a definite energy density—contains a definite number of ergs per cubic centimeter—and when this radiation falls upon a surface there is a definite flux of energy into that surface. The total intensity of such a flux on a unit area, can be completely specified in terms of ergs per second—or some other *unit of mechanical power* such as the watt. If the energy is wholly absorbed, and is converted only into heat, the power can be measured by calorimetric methods, *i. e.*, by ascertaining the rise in temperature of the absorbing body, the mass and specific heat of which are known. In practice, this is done, although not easily, with the help of a bolometer, a thermopile or a similar device. Determinations of this sort, when made for successive small wave-length ranges over the entire range of wave-lengths in the stimulus, would make possible an exact specification of the intensity, and would thus render the conditions of the experiment quite reproducible.

Two distinct, but closely related problems are involved in the control of visual stimulation intensities. The first is that of the equation of intensities, while the second concerns the establishment of a definite relation between at least one member of a set of such equations, and an *absolute* and reproducible *standard of intensity*.

In the study of visual response we are interested to determine the manner in which the various dimensions of the response depend upon each other and upon those of the stimulus. This dependency is complex in such a way that it can be represented symbolically by a polyvariable function, like $r = f(w, i, s, \cdots)$ where r is some one dimension of the response, and w, i, s, $\cdots$ are other dimensions, either of the response or of the stimulus. To determine the form of this complex function experimentally it is necessary to hold all of the variables on the right-hand side of the equation con-

stant, except one, and then to subject this one to variation. For example, to determine the effect of stimulus intensity, we may take any constant wave-length and try our experiment with different values of the intensity, or to find the influence of wave-length, we may select a definite intensity and vary the wave-length. In this latter procedure we are obliged to *equate* the intensities of the qualitatively different lights which we use.

For establishing such an equality of intensity the two general alternatives of photometry and radiometry are open. If the first method is employed the equation will be one of brightness; with the second method it will be one of radiant power (per unit area). The specific interpretation which is made of the term intensity will thus depend upon the method adopted.

The relation between the two types of equations should be borne carefully in mind. In the first place, when all other conditions are the same for the two equated stimuli—*i. e.*, for the same wave-length constitution, state of adaptation, position in the visual field, contrast, etc.—a photometric equation implies a radiometric equation. On the other hand, when the two stimuli are not similarly conditioned, in general this implication will not hold, and when the difference is one of wave-length a photometric equation may entail a relation between the radiometric intensity of one stimulus and that of the other, such that the quotient of these two intensities can have values ranging between zero and infinity, according to the relative positions of the two groups of wave-lengths in the spectrum.

Another point of importance is that, for certain standard and fairly representative conditions, the function—visibility curve—connecting radiant energy for equal photometric brightness, with wave-length has been accurately determined for the average or normal eye. This being the case, it is possible, for these conditions, to deduce one measure from the other; and the eye can be regarded as a selective radiometer having a known calibration curve. Conversely,

Ives and Kingsbury[1] have carried out extensive experiments on a so-called 'physical photometer' or 'artificial eye' in which an absorbing solution, or equivalent arrangement, having a selective transmission corresponding closely to the normal visibility curve, is placed between the light source and a thermopile. The results obtained, although radiometrically determined, are actually proportional to the photometric brightness of the stimuli measured. The visibility (or stimulus) coefficient, which is plotted—as a function of wave-length—in Fig. 2, is directly proportional to the quotient obtained by dividing the photometric measure by the corresponding radiometric measure.

The average visibility function may now be considered a reliable technical asset of the investigator in vision.[2] Strictly

[1] Ives, H. E., and Kingsbury, E. F., 'Physical Photometry with a Thermopile Artificial Eye,' *Phys. Rev.*, 1915 (2), 6, 319–334. Also, Ives, H. E., 'A Precision Artificial Eye,' *ibid.*, pp. 334–346.

[2] Average 'visibility curves' for normal cone vision and flicker photometry have been determined by Ives, Nutting, Bender and others. Ives employed 18 observers and later 25 more. Nutting used 21 in all. The relative visibilities (brightness/ relative energy) of various parts of the spectrum, as found by these two investigators, are given in the following table:

Wave-Length $\mu\mu$	400	410	420	430	440	450	460	470	480	490
(Nutting)	.002	.003	.008	.012	.023	.038	.066	.105	.157	.227
(Ives)	—	—	—	—	.029	.047	.073	.107	.154	.235
Wave-Length	500	510	520	530	540	550	560	570	580	590
(Nutting)	.330	.477	.671	.835	.944	.995	.993	.944	.851	.735
(Ives)	.363	.596	.794	.912	.977	1.000	.990	.948	.875	.763
Wave-Length	600	610	620	630	640	650	660	670	680	690
(Nutting)	.605	.468	.342	.247	.151	.094	.051	.028	.012	.007
(Ives)	.635	.509	.387	.272	.175	.104	.068	.044	.026	—

Wave-Length	700	710	720	730	740	750	760
(Nutting)	.002						
(Hyde and Forsythe)	.00282	.00137	.00068	.00033	.00017	.00008	.00003

Wave-Length	770
(Hyde and Forsythe)	.000015

Nutting's results are plotted in Fig. 2.

The values from 700 to 770 $\mu\mu$ are calculated from Hyde, E. P., and Forsythe, W. E., 'The Visibility of Radiation in the Red End of the Visible Spectrum,' *Astrophys. Journ.*, 1915, 42, 285–294. Nutting's results appear in his paper, 'The Visibility of Radiation,' *Trans. Illum. Eng. Soc.*, 1914, 9, 633–643; also in the *Phil. Mag.*, 1915,

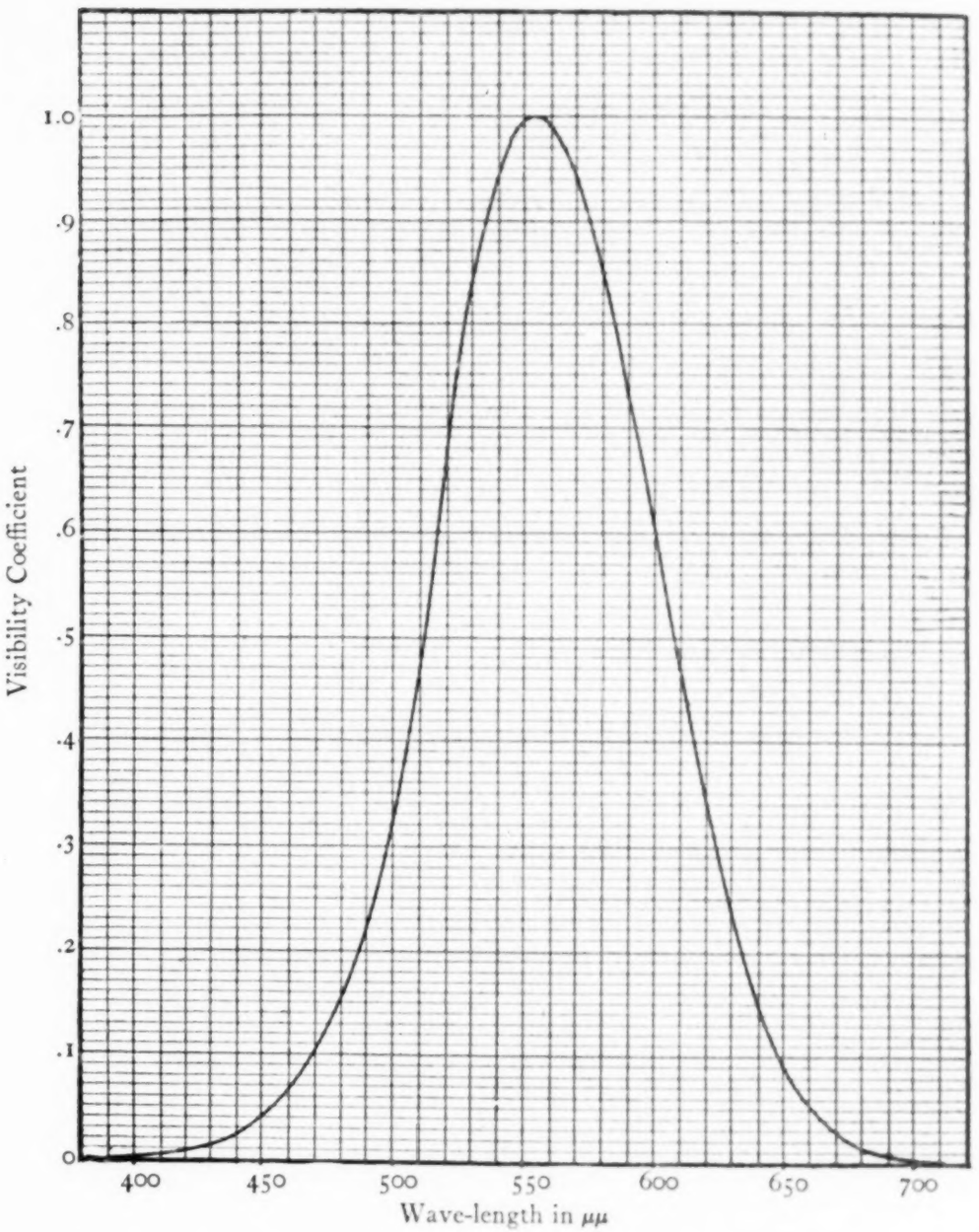


FIG. 2. The Visibility Curve According to Nutting. This curve is an accurate plot of the visibility values given below, representing the average results obtained from 21 subjects. If the photometric intensity of any 'homogeneous' visual stimulus is divided by the appropriate visibility coefficient (read off from the curve), and multiplied by the 'mechanical equivalent of light' (.00132 watts per lumen), the resulting value will be the radiometric intensity of the stimulus. By the converse procedure radiometric intensities can be changed into photometric values. Nutting's data were obtained by flicker photometry, and at a standard intensity of about 75 photons (see text).

speaking there will be a special visibility curve for each individual, for each species, for each absolute intensity of illumination of the retina, for each position on the retina, for each state of adaptation (whether general or specific) and for each method of photometry. However, comparison of the curves for different conditions does not, in general, reveal 'order of magnitude' discrepancies. It is very probable that the modal visibility curve for a given visual type is

(6) 29, 301. See also: Ives, H. E., 'The Spectral Luminosity Curve of the Average Eye,' *Phil. Mag.*, 1912 (6), 24, 853–864; and Bender, H., 'Untersuchung am Lummer-Pringsheimschen Spektralflickerphotometer,' *Ann. d. Phys.*, 1914 (4), 45, 105–144.

According to Nutting, the equation of the visibility curve is

$$(1) \qquad V = V_m R^a e^{a(1-R)} = V_m v_\lambda,$$

where $R = \lambda_{max}/\lambda$, λ_{max} being the wave-length for the maximum ordinate of the curve, approximately 555, and λ the wave-length for which the visibility is to be calculated. $a = 181$; V_m is the visibility at the maximum and e is the base of the natural system of logarithms. V_m is the ratio of the lumen to the watt (unit of power) at the wave-length having maximum visibility, the reciprocal of the so-called mechanical equivalent of light, for this wave-length. Since the problem of making an accurate determination of the mechanical equivalent of light has only recently been attacked, there is still considerable lack of agreement between authorities, as to its value. Nutting (*loc. cit.*) finds .00120 watts per lumen; Ives ('Luminous Efficiency,' *Electrical World*, 1911, 57, 1565–1568), calculating certain data of Nernst's, gets .00125. Ives, Coblentz. and Kingsbury ('The Mechanical Equivalent of Light,' *Phys. Rev.*, 1915, (2), 5, 269–294) give .00159; Langmuir ('The Characteristics of Tungsten Filaments as Functions of Temperature,' *Phys. Rev.*, 1916 (2), 6, 302–330), .00121; and Hyde, Cady, and Forsythe ('The Candle Power of the Black Body and the Mechanical Equivalent of Light,' *Jour. of the Franklin Inst.*, 1916, 181, 420–421), .00132. The last value, which was calculated on the basis of Nutting's visibility data, was obtained from especially satisfactory data.

The value of the expression, $R^a e^{a(1-R)}$, in Nutting's equation should be equal, for a given wave-length, to the corresponding value in the table, *i. e.*, it gives the relative visibility, or visibility coefficient, of the selected wave-length, the visibility at the maximum being taken as unity. When multiplied by V_m (757), the values in the table, or those obtained from the curve in Fig. 2, or from the equation, will yield the visibility in absolute terms, *i. e.*, in lumens per watt.

The lumen is the unit of luminous flux, and the candle-power of any light source in a given direction is equal to the number of lumens emitted by it per unit solid angle, in this direction. In visual psycho-physiology, however, we are concerned immediately, only with units of brightness, which involve the distribution of candle-power over a surface. Brightness is expressed in lumens per unit solid angle per unit area of radiating surface. Accordingly, the reduction of visual stimulus values from photometric to radiometric terms, means the conversion of *candles per square meter*, to *watts per steradian per square meter*. This latter quantity will be proportional, other things equal, to the energy impinging upon the retina, per unit time, per unit area.

practically independent of everything except the degree of participation, in the response, of rod process as compared with cone process. The problem of separating the effects contributed by these two distinct visual mechanisms, under all conditions, is one upon which further important advances are still possible. The standard visibility values now refer properly only to the normal, trichromatic, cone process.

Ultimately the technical definition of photometric brightness will probably be such that the brightness of any visual stimulus differing in quality from the standard will be determined only by its radiant power, and by the standard 'average visibility' of the given radiation. This standard specific visibility value will be determined by finding the mean values for a large number of normal human individuals under conditions most favorable for photometric comparison, and representing the most common circumstances of vision. On such a basis, with tested normal observers working[1] under the

To accomplish this reduction, the photometric value of the stimulus, expressed in candles per square meter, must be divided by the absolute visibility of the radiation constituting the stimulus. Thus, if b is the brightness measure in question, and v_λ is the proper visibility coefficient (obtained from the table or from the plot), we have, for watts/(steradian $\times$ square meter):

$$w = \frac{b}{V_m v_\lambda} = L\frac{b}{v_\lambda} = .00132\, b/v_\lambda, \tag{2}$$

where L is the mechanical equivalent of light. The same quantity, expressed in *ergs*/(second $\times$ steradian $\times$ square meter), would be

$$w' = 1.32 \times 10^4\, b/v_\lambda, \tag{3}$$

since one watt is equal to 10^7 ergs per second. The radiometric intensity of the radiation striking the retina can be calculated from w or w', by multiplying either of these quantities by a factor, the magnitude of which is determined by the size of the pupil, the focal length of the eye, and other ocular variables (*vide infra*).

[1] In order to select observers whose color vision approximates the established averages, H. E. Ives has devised color filters intended to provide a simple and effective test of the normality of any individual. See his papers, 'On the Choice of a Group of Observers for Heterochromatic Measurements,' *Trans. Illum. Eng. Soc.*, 1915, 10, 203–209; 'Experiments with Colored Absorbing Solutions for Use in Heterochromatic Photometry,' *ibid.*, 1914, 9, 795–814; 'Additional Experiments on Colored Absorbing Solutions for Use in Heterochromatic Photometry,' *ibid.*, 1915, 10, 253–259; 'A Method of Correcting Abnormal Color Vision and Its Application to Flicker Photometry,' *ibid.*, 1915, 10, 259–271. The Ives-Kingsbury test filters were employed by Crittenden and Richtmyer in their recent extensive investigations of flicker photometry.

specific standard conditions visual photometry can be construed as a special, convenient method of radiometry.

Ferree and Rand[1] claim that for the purposes of scientific physiological optics, the intensity of visual stimuli should be measured, and equated, in radiometric and not generally in photometric terms. If this is taken to mean that, at least with present methods, the ultimate basis of standardization of intensity measures is radiometric, the claim may be admitted. If, on the other hand, it is meant that direct radiometry is required in the psychological laboratory, for the immediate control of visual stimulus intensities, and that photometric measurements and equations should be rejected, we must certainly dispute the contention.

It would even be possible to argue that the radiometric treatment of the intensity of the stimulus is not only technically difficult, and perhaps lacking in immediate interest for the majority of problems, but is arbitrary. To measure radiation in terms of energy is to determine how much heat it can generate. Why not consider radiation in its immediately interesting context, and try to discover how much luminosity, or visual brightness, it can generate? In other words, let us replace the thermopile by a retina, and find the law of distribution of brightness in the spectrum of the stimulus which we are using. Then we shall be able to select visual stimuli of different wave-length, but of equal brightness.

From a strictly physical point of view the argument that the standardization of visual stimuli in terms of the temperature effect of the radiation is of no more fundamental significance than its standardization in terms of brightness, cannot be considered valid. In the first place, if we measure radiation intensity in terms of energy, and employ ideal instruments, our results will be independent of the instruments themselves; every radiocalorimeter which will absorb

[1] See Rand, G., 'The Factors that Influence the Sensitivity of the Retina to Color, etc.,' *Psychol. Mongr.*, No. 62, 32–40, 1913. Also: Ferree, C. E., and Rand, G., 'A Note on the Determination of the Retina's Sensitivity to Colored Light in Terms of Radiometric Units,' *Amer. J. of Psychol.*, 23, 328–333.

all of the radiation and convert it all into heat will give us the same measure, and the measure can never be greater than this. In the case of the retina and brightness, however, everything depends on the instruments, and there is, so far as we are aware, no maximally efficient instrument. In general, the energy of a physiological response is not derived from the stimulus, but is merely released by it. Only an almost infinitesimal fraction of the total gamut of electromagnetic waves is capable of producing any brightness at all. There is nothing inherently distinctive about this fraction, either, so that, strictly speaking, its brightness, or its luminosity, is a property of the eye and its appendages rather than of the radiation itself.

Moreover, a measure of brightness cannot be regarded as being in absolute units unless it is referred to a definite radiant power (by use of the standard visibility values). It may be possible, ultimately, to measure the intensity of physiological —and even psychological—response in absolute units, but there is no established technique for doing this at present, so far as the results of photometry are concerned. If it were certain, or even likely, that this response intensity was the same for all individuals for a given intensity of the photometric standard, the response to the standard could be adopted as an absolute norm. As matters stand it can only be regarded as a relative norm.

In spite of all these objections, however, it is the writer's opinion that, in general, the photometric equation of intensities is preferable to the radiometric. This opinion has both a theoretical and a practical basis. The latter consists primarily in the extreme difficulty of making reliable radiometric measurements, as compared with the ease with which photometric equations are established, especially when the flicker method (*vide infra*) is employed. Radiometric and photometric measurements have, in general, about the same precision, somewhat better than one per cent. However, radiometers measure indiscriminately the energy of all types of radiation, whether visible or not, so that unless great care is taken to eliminate infra-red and ultra-violet rays, the

results are apt to be wholly misleading, considered as estimations of stimulus intensity, since these special rays are not visual stimuli.[1] Closely related with this is the fact that stimuli equated in energy over the whole spectrum will have a brightness so disproportionate as, in many cases, to make their visual comparison almost impossible. For example, under these conditions, a stimulus of wave-length 550 $\mu\mu$ would be about ten thousand times brighter than one of wave-length 750 $\mu\mu$. One of these stimuli might be just at the threshold, and the other would then be dazzlingly bright.

The purely practical difficulties of radiometry can be conquered by a careful technique. However, considering the interconvertibility of photometric and radiometric measurements, when the former are made by normal observers, it would seem unnecessary for the psychologist to trouble himself with these delicate procedures. *Moreover, whether the observers are normal or abnormal, there are certain theoretical advantages possessed by photometric equations, which cannot be ascribed to radiometric equations.*

Visual response consists of a series of stages or phases following each other in time, each phase having a number of more or less independent dimensions, the exact values in which, however, are determined primarily by the values of corresponding dimensions in the preceding stage. These stages, in their temporal order are, roughly: (1) visual object, (2) radiation from the object entering the eye, (3) the retinal image, (4) the receptor process, (5) the neural stimulation, (6) the afferent impulse, (7) the adjustor (or central) process, (8) the efferent impulse, (9) the effector process. In addition to these, and a function of some, and perhaps all, of the stages, there is: (*a*) visual experience. The values of the variables in each stage at any moment may be regarded as mathematical functions of the values of the variables in preceding stages at earlier moments.

[1] This statement may perhaps be questioned as applied rigorously to the ultra-violet, but it is the infra-red rays which are most bothersome in the radiometric measurements of visible radiation.

Now for the theoretical analysis of the total process of vision, which must be regarded as the ultimate scientific aim, the problem of the interrelation of what may be called the internal *factors* of the response (succeeding and including the receptor process), is probably of more importance, and is certainly far more difficult, than that of determining the relation between the stimulus variables (1 to 3) and certain internal factors. To separate the effects of the various variables in any internal stage of the response, certain of these variables, directly, should be held constant while others are subjected to change. It must be true that any two stimuli which produce the same effect upon a retinal receptor will have an equal value for all succeeding stages of the response. This will probably hold approximately, also, when the similarity of effect applies to only one dimension of the receptor process, if the subsequent influence of this dimension is considered in isolation from that of the others. The known facts provide us with some guarantee that photometric equations do establish such an equivalency—approximately—for the general dimension of intensity of the response, whereas there is no doubt whatsoever that stimulus energy equations fail in this respect.[1]

Such photometric equations would be relatively independent of specific, individual, and momentary variations in the sensitivity of the visual system, and hence would correct automatically for these variations, provided, of course, that the equations are made by the subject for whom the measured lights are later to be employed as further stimuli. Among themselves a system of intensity measures based upon photometry by *individuals selected at random*, must of course be considered as constructed with reference to any one subject's absolute sensibility to the standard of luminous intensity, as a norm.

However, when photometric equations are made by a

[1] The exact physiological nature of response intensities, apart from experienced *luminosity*—or other sensory attributes—remains, of course, somewhat vague. It may be a question of equality of reaction velocities, equality of energy released or absorbed per second, or—what is more likely—the concentration of certain ions in the respector cells.

tested, normal observer,[1] they refer back automatically to radiation intensities as a basis, since photometric values obtained under standard conditions must be equal to the corresponding radiometric values, multiplied by the appropriate visibility factor. Consequently, the radiant power of stimuli of wave-length constitution different from that of the standard light can be obtained by dividing the photometric quantity by the factor in question. If a normal observer is not to be found, methods can be applied for correcting the measurements so that they will coincide approximately with the normal.[2]

It is perfectly obvious, of course, that certain problems—such as those of visibility—involving the relationship between the receptor process and the stimulus, must be settled on the basis of direct energy measurements. Our contention here—in summary—is merely that such problems form a relatively small part of the whole group of questions faced by the psycho-physiologist in vision, and that for the remaining group, energy equations will yield results difficult, if not impossible, of interpretation.[3] Moreover, the existence at present of reliable determinations of visibility and of standard methods for applying them to photometric results makes radiometric and photometric measurements largely interconvertible. The simple technique of photometry recommends it to the psychologist, and at the same time permits him to express the conditions of his observations in such a manner that they can be interpreted and reproduced by others.[4]

[1] The appropriate tests have been described by Ives. See the references above.

[2] See Ives, *Trans. Illum. Eng. Soc.*, 1915, 10, 259–271. Also Crittenden, E. C., and Richtmyer, F. K., 'An "Average Eye" for Heterochromatic Photometry, and a Comparison of a Flicker and an Equality-of-Brightness Photometer. *Trans. Illum. Eng. Soc.*, 1916, 11, 331–372.

[3] In the writer's estimation, the questions raised primarily by Ferree and Rand, *viz.*, the peripheral limits of color sensitivity in the retina, fall mainly in the group where energy equations will complicate, rather than simplify the investigation. *Cf.* Baird, J. W., 'The Phenomena of Indirect Color Vision,' *Psychol. Review*, 1914, 21, 70–79.

[4] It should be borne in mind that ordinary direct radiometry, as carried out by means of a thermopile or bolometer, yields relative energy measures, only. The technique of absolute radiometric measurements, or radiocalorimetry, is even more difficult than that of relative methods.

III. The Problem of Heterochromatic Photometry, and the Justification of the Flicker Photometer

If the procedure of photometry involved in general only the equation of stimuli having the same energy distribution curve in the spectrum and hence the same color, the problem would be a very simple one. As a matter of fact, it is very seldom that two visual stimuli to be equated have the same distribution curve, and this, of course, is never the case when the main conditions which we have been considering above are in question, for under such conditions radiometry and photometry are *equivalent* methods. Moreover, photometry in general is color photometry, since none of our light sources are strictly 'white' and even sunlight varies in hue.

The problem of the proper method for the equation, in respect to brightness, of two lights of different color, has been under discussion for many years, but has never received more attention than is being devoted to it at the present day. This problem is partly experimental and partly logical, and more progress has been made on the experimental than on the logical side of the question. The latter aspect of the problem concerns primarily the definition of 'equal brightness,' and the establishment of a scientific criterion for choosing a satisfactory method of heterochromatic photometry.[1]

The term 'brightness' may now be regarded as having been definitely appropriated by the photometrician to designate that aspect of illumination questions which has immediate reference to the effect of a given stimulus on a given eye. The brightness of an illuminated surface depends upon a point of view. When lights of different colors are compared the brightness must also depend upon the visibility curve of the eye, and this visibility curve will not, in general, be the same for different methods of heterochromatic photometry. *It would seem advisable to employ the term brightness to express*

[1] The criteria have been considered by Ives, *Phil. Mag.*, 1912 (6), 24, 153–157. An excellent discussion of the problem of heterochromatic photometry will be found in M. Luckiesh, 'Color and Its Applications,' 1915, Chap. IX. This book contains much useful data for the investigator of vision.

the photometric value obtained for any visual stimulus by the standard method of photometry. For example, if we adopt the flicker method as our standard procedure the flicker value of a visual stimulus will be its brightness.[1]

Ordinary or direct comparison photometry is based upon an equation of luminosities. The criterion of 'equal luminosity' is not ambiguous when the lights to be compared are of the same color (hue and saturation) since in this case the task of the photometrician is merely to find two amounts of radiation which produce entirely similar sensations. However, when the two radiations are such as to condition a noticeable difference in color, it is necessary to discriminate inspectively between the experiential dimensions of hue and saturation, on the one hand, and that of *luminosity* on the other.

Now there seems to be a general psychological law that the distinctness of any experiential (or qualitative) dimension changes in parallel with the degree of similarity of two compared experiences in all other dimensions. For example, if luminosity, hue and saturation are three dimensions of a visual sensation (*per se*) the threshold for the perception of a difference in luminosity between two sensations will be greater the greater the concomitant differences in hue or saturation, or both. This principle may depend upon a weakening of our powers of discrimination or it may indicate that the dimensions, as such, are to a certain degree mutually dependent and unreliable. In other words, the meaning of the term 'equal luminosity' may become *ambiguous* in proportion as two compared sensations differ in color.[2]

[1] Since the flicker value and direct comparison value of a given colored light do not, in general, agree, this definition would mean, on the basis of flicker photometry, that equally bright lights do not always generate equal luminosities. This usage of 'brightness' of course conflicts with some traditional phrases, such as 'equality of brightness,' but is in line with the modern development of photometric nomenclature.

[2] This conception may perhaps be expressed by saying that a system of ideal Cartesian axes for the determination of values in these dimensions would not be a set of mutually perpendicular *lines* intersecting in a single point, but would consist of a group of (perhaps truncated) *cones*, with their axes perpendicular and with their apices meeting at the origin of coördinates. This would mean that all differences in luminosity, hue, saturation, tint, etc., are to a certain extent indeterminate, and that

The hypothesis that in heterochromatic comparisons of luminosity it is not essentially the process of judgment but rather the conception of the dimension of luminosity itself which is uncertain, surely represents the psychological facts of the case very well. Relations exist which can be judged categorically as *differences* in luminosity, but it is never possible to make a categorical judgment of *equality* of luminosity. The truthful judgment is always: "I cannot tell whether they are equal in luminosity or not." Langfeld[1] and others have shown that the results obtained by heterochromatic comparison depend radically upon the 'attitude of the observer,' or upon the 'criterion' for equality of luminosity which is adopted. This 'criterion' would amount, on our theory, to a redefinition of the term 'luminosity' for the special comparison involved.

The existence of this uncertainty as to the meaning of the term 'equal luminosity' for lights of different color should lead one to conclude that equality of luminosity, and consequently the method of direct photometric comparison, cannot be regarded as furnishing a satisfactory test of equality of brightness for such lights. The uncertainty of course makes itself evident objectively in the lack of precision of photometric measurements made by this method, and in the lack of agreement between different normal observers.

this indetermination becomes greater in any given dimension the greater the established differences in other dimensions. The facts are such that this hypothesis involves us in fewer serious assumptions than one which refers the difficulty to a fallibility of the discriminative function.

If we adopt the hypothesis in question, it follows that the term 'equal luminosity' necessarily becomes more and more ambiguous the greater the difference in hue and saturation, between two compared sensations. In other words, 'equal luminosity' cannot represent any definite condition of affairs, except the absence of 'unequal luminosity,' a requirement which could be satisfied in many different ways. On this basis, since the photometric equation of brightnesses depends upon the equation of sensory luminosities, the ordinary procedure of 'direct comparison,' or 'equality of brightness,' photometry would tell us unequivocally when two brightnesses were unequal, but not unequivocally when they were equal.

Recent experiments by the writer show that with large color differences between compared visual fields, the just noticeable difference in brightness may exceed 20 per cent. See 'The Heterochromatic Brightness Discrimination Threshold,' *Journal of the Franklin Inst.*, 1916, 182, 112–115.

[1] Langfeld, J. S., 'Ueber die Heterochrome Helligkeitsvergleichung,' *Zeitschr. f. Psychol.*, 1909, 53, 113–179.

If we reject the method of direct comparison we must cast about for another procedure which measures approximately the same quantities, but which depends upon more definite psychological criteria, and possesses a better objective precision. A large number of careful experiments, due primarily to H. E. Ives,[1] have proved unquestionably that *flicker photometry* satisfies this requirement. It has been shown by Ives that (1) "the flicker method is more sensitive than the equality of brightness method, where different coloured lights are compared," and that (2) "the results by the flicker method are more reproducible than those by the equality of brightness."[2] Crittenden and Richtmyer, in recent work, find the mean variation of the results of 114 observers by the 'equality of brightness' method to be 1.9 per cent. and by the flicker method .6 per cent. for the same stimuli. They say: "With regard to certainty of measurement the flicker photometer shows a decided advantage even with small color differences. With more experienced observers, specially selected, this advantage would probably be materially reduced, but would not be entirely lost, because even when an observer makes consistent settings on the equality photometer the relation of his settings to those of the normal observer is uncertain. . . . with the flicker any observer of fair ability can make definite sets even with large color differences whereas on the Lummer-Brodhun ['equality of brightness'] photometer it is only the exceptional observer who can do so. . . . The flicker photometer affords a means of relatively precise comparison between lights of all degrees of color difference, and makes possible the use of test readings for which average values, which should be highly reproducible, can be established."

Ferree and Rand[4] have attacked the flicker method on

[1] Ives, H. E., 'Studies in the Photometry of Lights of Different Colours,' *Phil. Mag.*, 1912 (6), 24, 149–189, 352–370, 744–751, 845–864. See also the recent elaborate investigations, with 114 subjects by Crittenden, E. C., and Richtmyer, F. K., 'An "Average Eye" for Heterochromatic Photometry, and a Comparison of a Flicker and an Equality-of-Brightness Photometer.' *Trans. Illum. Eng. Soc.*, 1916, 11, 331–367.

[2] *Loc. cit.*, p. 177.

[3] Ferree, C. E., and Rand, G., 'A Preliminary Study of the Deficiencies of the Method of Flicker for the Photometry of Lights of Different Colors,' *Psychol. Rev.*, 1915, 32, 110–163.

the ground that the results which it yields disagree with those of the 'equality of brightness' procedure. They explain the discrepancy in terms of the different rates of growth and decay of sensation for the different colors. This criticism of the use of the flicker method—and the considerations on which it is based are not new[1]—presupposes that the object of a method of photometry is to measure light in terms of equated luminosities, and that to justify the flicker procedure, it is necessary to prove that the *flicker value* of a light agrees within the limits of precision of the measurements with its value as determined by direct comparison. It is one thesis of the present article that this presupposition is arbitrary and scientifically questionable.

In the first place, it must be admitted that an acceptable method of photometry must yield results which agree *approximately* with those of the 'equality of brightness' procedure; the disagreement should certainly at no point be greater than a single order of magnitude. The reason for this requirement is to be found in our conviction that luminosity is closely proportional to the intensity of the response, and to the utility of the radiation, the variables in which we are fundamentally interested. However to require accurate agreement between the two sets of results would be unreasonable, first, because of the relative ambiguity of 'equality of luminosity,' and secondly, because it is improbable that luminosity or any other property of the response which we may select as a basis for establishing a photometric balance, can be considered immediately indicative of all phases of the intensity of the response, without correction for the special conditions of its utilization.

Ferree and Rand do not claim to be pioneers in the proof that the results of the flicker method and that of direct comparison do not agree. Ives[2] found that the curves showing the distribution of brightness in the spectrum, as determined by the two methods, differed in a number of very

[1] See Luckiesh, M., 'On the Growth and Decay of Color Sensations in Flicker Photometry,' *Phys. Rev.*, 1914 (2), 4, 4–6.

[2] *Loc. cit.*, pp. 177–178.

definite ways. However, in general these differences were small. Crittenden and Richtmyer say: "In regard to relative results there appears to be no room for doubt that for sources having relatively high intensity at the blue end of the spectrum the values given by the flicker photometer as here used depart appreciably from those obtained with the Lummer-Brodhun as used in common practise, the difference being of the order of 2 per cent. at the higher efficiencies reached by the present gas-filled lamps."[2]

Considering the probable complexity of the processes of growth and decay of color sensation it would indeed be surprising if the results obtained by the flicker photometer depended directly, without correction, upon the luminosity value of a light. Very interesting theoretical studies on this question have been made by Ives and Kingsbury.[2] Successive contrast must also introduce complications,[3] just as simultaneous contrast must influence the results of direct com-

[2] The same authors continue: "It is, however, hardly proper to assume that the results obtained by either photometer are 'right' and anything different is 'wrong'; the equality-of-brightness method of measurement is undoubtedly more closely related to the way in which the light is used, but it is by no means established that the method correctly indicates the relative usefulness of two kinds of light. It must be recognized that there is no one definite 'correct' ratio between the intensities of two lights of different color. . . . The specification of conditions of measurements must be more or less arbitrary, and the results obtained cannot be expected to be an exact indication of the value of different kinds of light under different conditions. Before we shall know much about the relative usefulness of different kinds of light much more experimental work must be done; an important requisite for such investigations or any others involving the comparison of the intensity of lights by very different color is a method which will enable different experimenters to make consistent measurements of the quantity which must serve as a basis for the comparison of their results. The usual equality-of-brightness method of comparison certainly does not fulfill this requirement; the flicker photometer at present is the most promising method available." "Comparison of actual tests made in the routine work of the laboratory shows that even with relatively small color differences a given accuracy of reproduction of results requires several times as many measurements with the equality-of-brightness or the contrast photometer as with the flicker; moreover the tests considered were made by observers who had had much experience with the contrast photometer and very little with the flicker."

[2] Ives, H. E., and Kingsbury, E. F., 'The Theory of the Flicker Photometer,' *Phil. Mag.*, 1914 (6), 28, 708–728. This article represents clearly the correct way to attack visual problems, and contains concepts of fundamental importance for a large number of visual phenomena.

[3] Cf. Luckiesh, *loc. cit.* p. 6–8.

parison.[1] The theory of the flicker photometer as developed by Ives and Kingsbury, indicates that its results should approach asymptotically those of the direct comparison method as the intensity of stimulation increases. This deduction is in harmony with fact.

The essential point to be established, however, is this: the one necessary requirement of a method of measurement is that it shall permit the accurate reproduction of experimental conditions. As shown by the work of Ives and other modern students of the problem of heterochromatic photometry, this requirement is met by the flicker method, and not by any other procedure which has been adequately tested.[2] As a consequence, we are forced at present to accept the flicker method as our standard procedure, and to define photometric brightness in terms of its results regardless of the fact that these results differ somewhat from those obtained by the criterion of equal luminosity.

It is possible that we shall ultimately find some reliable method for measuring directly what may be called the *true response intensity*, for a specified stage of the response. The exact functional connection between this quantity and flicker value can then be determined, so that the true intensity can be deduced from the flicker value. Possibly the nature and magnitude of this correction can be deduced from the theory of the flicker photometer. For many purposes, however, the conversion of true physiological intensity would prove useless, since a knowledge of the laws connecting other properties of stimuli, *e. g.*, such as acuity values, with flicker value should be as serviceable as a knowledge of the relation between these properties and true intensity. For theoretical purposes, of course, equations of true intensity are highly desirable, but it is by no means certain that the method of direct com-

[1] See Bell, L., 'Some Factors in Heterochromatic Photometry,' *Electrical World*, 1912, 59, 201–203.

[2] Ferree ('A New Method of Heterochromatic Photometry,' JOURNAL OF EXP. PSYCHOL., 1916, 1, 1–13) has recently proposed a new procedure for which he claims remarkable accuracy. Since the method is a peculiar one, not immediately suggestive of reliability, it will have to be more carefully investigated before it can be taken seriously.

parison would not demand corrections, in this respect, as great as those required by flicker. Moreover the flicker results furnish a reliable measure upon which to base such a correction, which cannot be said of the results obtained by direct comparison.

As already pointed out, the general problem of photometry is that of establishing heterochromatic equations, since color differences are the rule rather than the exception, for the lights which need to be compared. However, when the color difference is less than some critical amount, the method of direct comparison becomes more sensitive than that of flicker. But, as color difference disappears, the results of the flicker procedure approach identity with those of direct comparison, so that for lights differing only slightly in color from the standard it is immaterial whether we define photometric brightness in terms of flicker or of equal luminosity values, and in such case—as in general—we will naturally employ the method which is the most reliable.

IV. The Influence of the Pupil on the Intensity of the Visual Stimulus, and the Definition of a Standard Unit for Specifying the Intensity of Visual Stimulation

In a previous article[1] the writer has emphasized the importance of the artificial pupil in the control of the intensity of visual stimuli. The actual visual stimulus is the retinal image, and the illumination which this image represents is always proportional to the area of the pupillary opening. The normal range of variation of pupillary area is from 1 to about 16, so that neglect to control the size of the pupil would introduce a factor of uncertainty into our measurements of the intensity of the visual stimulus—or our equations of response energies—perhaps as great as 1,600 per cent. This is not large compared with the range of external illuminations, but it is enormous compared with accuracy with which intensities can be determined by photometry.

[1] Troland, L. T., 'The Theory and Practise of the Artificial Pupil,' *Psychol. Rev.*, 1915, 22, 167–177.

All careful workers in vision have recognized this fact, and have taken pains to keep the pupil opening constant, and to state the pupillary diameter as one of the conditions of their experiments. This is true of Ives's studies on the flicker photometer, of Nutting's determination of the visibility function, and of the earlier careful measurements of König on visibility and difference threshold. There may be some problems in vision for which the *order of magnitude* of the intensity alone is of importance, but with entire neglect of the pupillary size we cannot even insure a knowledge of the exact order of magnitude of the retinal illumination. In the present state of visual science it is not safe to assume that a determination of the order of magnitude of the intensity, or an establishment of intensity equations to a first order of approximation, is generally adequate.

It is perhaps needless to say that these considerations apply with equal force both to radiometrically and photometrically determined intensities.

When the pupil size is known it is convenient to express the intensity conditions in terms of unit pupil area. This is done by both Ives and Nutting in the researches already referred to. In an extensive monograph on the laws of color adaptation, yet to be published, the present writer has expressed his intensity measures throughout in terms of a unit involving the pupillary area, and has proposed that this unit, called the *photon*, be adopted as the standard means of specifying the photometric intensity of visual stimulation conditions.

The definition of such a unit involves a number of independent considerations. The first of these concerns the mode of expressing what may be termed the *external intensity* of the stimulus. As a rule this external intensity is given, in descriptions of visual work, in terms of *meter-candles*. This is, of course, a mistake, since the meter-candle is a unit of *illumination*, *i. e.*, it measures the light *falling upon* a surface, whereas for purposes of visual experimentation, it is the light (density) *leaving* the surface *in the direction of the eye* which, alone, is of importance. To deduce this quantity from the illumination it is necessary to know the coefficient

of reflection, and the diffusing power of the surface. The quantity in question is called the *photometric brightness* of the surface in the given direction, and is measured in candles per unit area, or in *lamberts*. It is the only external photometric quantity which is of importance to the visual physiologist, since it is the brightness which determines the illumination of the retinal image.

It would be supererogatory to discuss this question of the measurement of the external intensity of the stimulus further in this paper, since it has been thoroughly treated in the recent and extremely useful article by Cobb, already referred to.[1] Suffice it to say that the first step is to determine this intensity in (let us say) candles per square meter, from the exact point of view to be employed by the subject in the experiment.

This determination should be made by a normal subject under standard conditions (or else corrected to the normal) and, in general, by the use of a flicker photometer. The photometer should be of the Whitman disk type, in which the alternation consists of an instantaneous substitution of the measured light for the standard at any one point of the retina, and in which the periods of presentation of the standard and the measured light are equal. Moreover, the speed of the photometer should be adjusted so as to give maximum sensibility, *i. e.*, should not be increased beyond the point at which color-flicker just disappears.[2]

The photometric equation should be established with the eye centered in front of an artificial pupil sufficiently small to prevent oscillations of the natural pupil from cutting off any of the light.[3] This pupil may be of any shape, provided its area is known, and in the standard case its axis should coincide with the line of sight. For stimuli produced by simple transmission or reflection arrangements, the circular pupil is preferable, while for spectral stimuli in which an

[1] *Psychol. Rev.*, 1916, 23, 71–89.

[2] The writer is at present making careful measurements of this critical speed for the spectral colors at various intensities, and with standard lights of various colors. See *Journal of the Franklin Inst.*, 1916, 181, 553–555.

[3] See the writer's article on the artificial pupil.

image of a slit is thrown upon the eye, a square, or otherwise rectangular, opening is more convenient and reliable. In the case of a slit image it is not necessary—in determining the photon value—that the image should fill the pupil, provided the light from the standard fills it. To establish a photometric equation the two retinal illuminations must always have the same brightness, and any increase in the effective pupil area for one will thus automatically be compensated for by an inversely proportional decrease in the external intensity needed for the equation.

Let us suppose that the measured brightness is b candles per square meter, and that the area of the pupil is p square millimeters. Then if r is the illumination of the corresponding retinal image (in meter-candles), we have

$$r = jpb, \tag{4}$$

where j is a factor depending upon the reflection, absorption and scattering of light in the eye, upon the angle of incidence of the rays with reference to the line of sight, and upon other influences to be considered below.

Suppose, now, that in an ideal case both p and b are equal, separately, to unity. Obviously in this case the value of the product, pb, will also be unity. For a given value of j this condition represents a definite retinal illumination, which will be duplicated whenever pb has the value of unity, whether or not the individual components have this value. Let us arbitrarily select this convenient intensity, for certain standard conditions, to be specified more in detail below, as the unit of physiological stimulus intensity, which may be known as the *photon*.

It should be clear from the above that if the intensity conditions of stimulation in visual experiments are expressed in photons they are unequivocally determined and can be directly compared, regardless of the actual pupillary size which was used, or the actual external brightness. To obtain this photon measure approximately it is only necessary to multiply the photometrically ascertained brightness—in candles per square meter—by the area of the pupil—calculated in square millimeters.

In order to determine accurately the physiological intensity of a stimulus surface under any desired condition, it is necessary to correct for variations in the factor j. The value of this factor may be regarded as summing up the

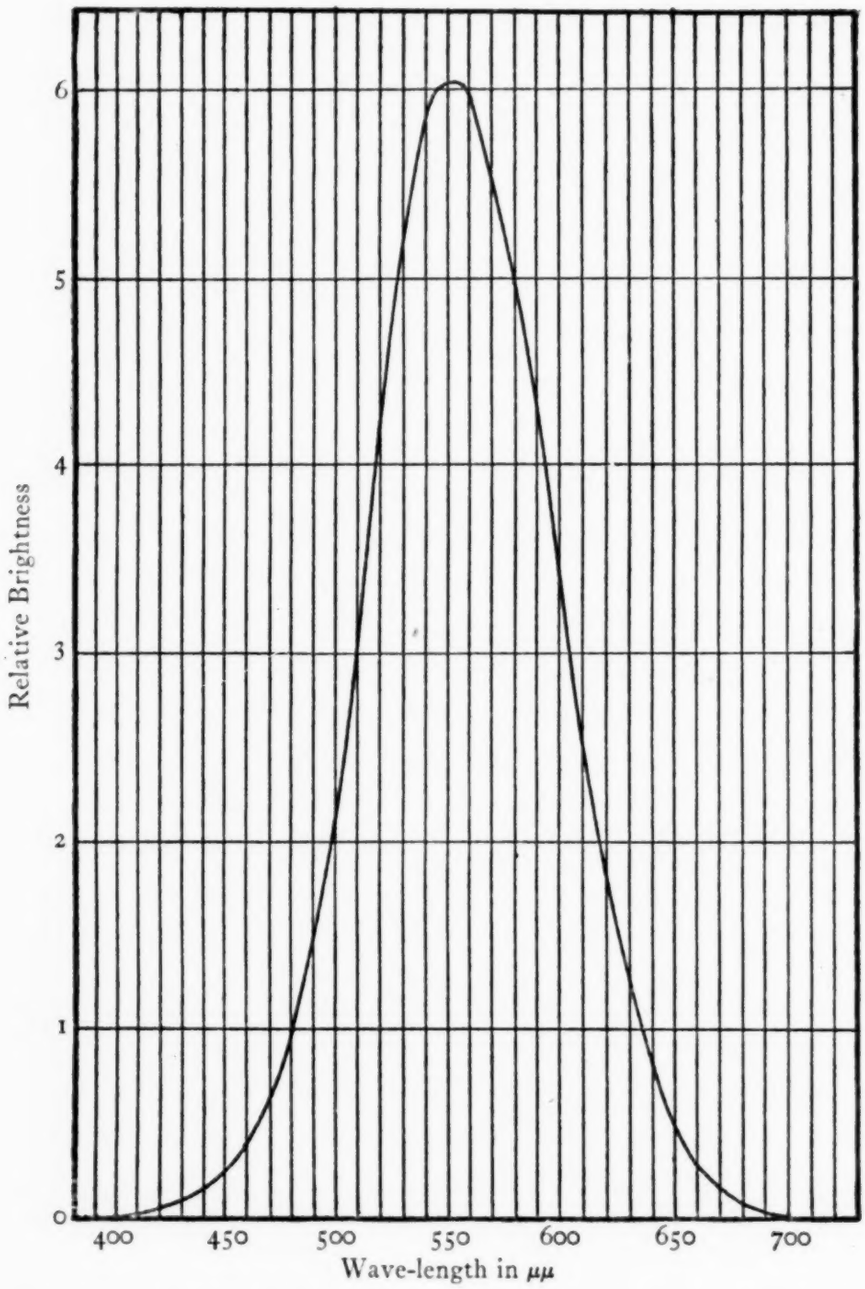


FIG. 3. Brightness Distribution Curve of the Light from a "Black Body" at 6200° Absolute. This curve was obtained theoretically by multiplying each ordinate of Fig. 1 by the corresponding ordinate of Fig. 2. It will be seen that it is practically identical in form with the visibility curve.

influence upon retinal illumination of variables other than the external brightness and the area of the pupil. The most important of these variables are the angle made by the direction of the stimulus surface with the line of sight, and the distance of the artificial pupil from the nodal point of the eye.

If ϕ is the angle in question (see Fig. 4) and the plane of the pupil is perpendicular to the line of sight, j must contain the factor: $\cos \phi$. On the assumption that intensity differences less than one per cent. may be neglected, the influence

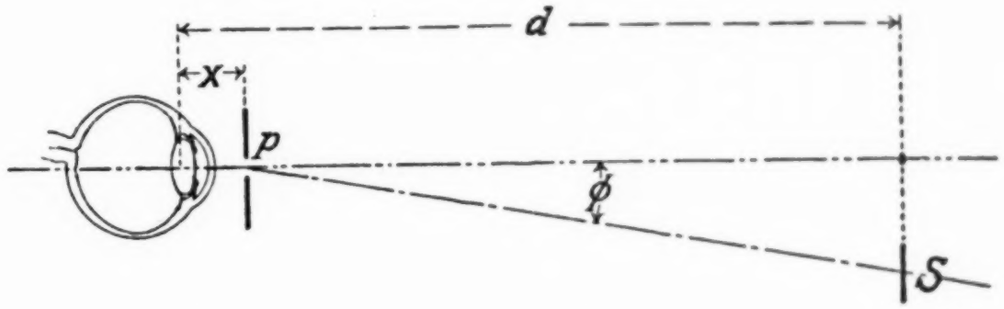


FIG. 4. The Influence of the Position of a Stimulus Surface and Artificial Pupil on the Intensity of the Retinal Image. See the text.

of angle can be disregarded, unless ϕ is greater than 8°, since the cosine of 8.1° is .9900. In the paper already referred to, the writer has estimated that the limiting angle for the use of the ordinary artificial pupil is about 53°. The cosine of 53° is .6018, the reduction in the physiological intensity of a stimulus viewed at this angle therefore amounting to about 40 per cent. of its value for direct vision.

For larger angles than this it is still possible to use the principle of the artificial pupil by means of an optical train which forms a sharp image of a small diaphragm within the natural pupil. This device has been employed by Cobb,[1] although not for peripheral stimulation. In an arrangement of this sort the area of the effective pupil depends entirely upon that of the diaphragm, the image of which falls within the natural pupil, but may be considered equivalent to the

[1] Cobb, P. W., 'The Influence of Illumination of the Eye on Visual Acuity,' *Amer. Journ. of Physiol.*, 1911, 29, 87.

pupillary area which was employed in photometering the light. In this case—provided, of course, the image clears the iris—there is no cosine effect.

It is possible to avoid the cosine correction in the use of the ordinary artificial pupil if the pupil is placed normal to the line passing through center of the stimulus surface and the nodal point of the eye, provided the surface in question is small. However, such an arrangement of the pupil presents no practical advantages, but only difficulties.

There is, of course, also a cosine effect when the natural pupil is employed, although it cannot be calculated directly from the external visual angle of the rays, on account of the refraction which occurs at the cornea. This tends to reduce slightly the average angle at which the rays strike the natural pupil, so that the reduction of intensity will not become appreciable at so small an external visual angle as with the artificial pupil.

In addition, for both natural and artificial pupils, there are other influences affecting the retinal illumination. The loss of light by reflection at the various refracting surfaces of the eyes increases with the angle at which the light impinges upon them. Besides this, the light strikes peripheral regions of the retina obliquely to the surface. Both of these effects reduce the peripheral retinal illumination. The peripheral regions, however, are reached by the light after passing through a somewhat thinner layer of absorbing material than is the case for the central regions, which would involve a slight relative increase in the illumination.[1] All of these factors would have to be taken into consideration in determining an accurate value for the physiological intensity of stimulation in the extreme periphery, although they can safely be neglected for fixated fields of 20° or smaller.

If the *photon* should be adopted as the universal unit for expressing the intensity of retinal stimulation it would of course be necessary to reduce the intensity to terms of this unit even when an artificial pupil is not used. This can be

[1] This is not by any means a complete catalogue of the factors influencing the intensity of the light which gets to the retinal receptors, but it will probably suffice for the present discussion of approximations.

accomplished, approximately, by multiplying the photometric brightness of the stimulus by the average apparent size of the natural pupil—the so-called *Eintrittspupille.*

Analysis shows that the illumination of the retinal image is not wholly independent of the distance between the artificial pupil and the eye. In general the illumination of the retinal image is nearly independent of the distance of the *object* from the eye.[2] This is a result of the fact that the area of the image changes in close proportion to the total light flux entering the pupil from the object. However, when the eye moves relatively to an artificial pupil, and the object is stationary with respect to the pupil, this compensation does not occur, since the total flux remains the same, while the area of the image alters.

If f is the focal length of the eye, d the distance of the stimulus surface from the nodal point of the eye, and x the distance between the artificial pupil and the nodal point of the eye, we can argue as follows. Take S as the area of the (small) stimulus surface, and b, as its brightness. Then the area of the retinal image will be Sf^2/d^2, and if p is the area of the artificial pupil, the total flux passing through it will be $Sbp/(d - x)^2$. Consequently, the illumination of the image must be proportional to

$$\frac{bpd^2}{f^2(d - x)^2}.$$

It is seen that if x is small compared with d its influence can be neglected.

Assuming that the effect of x upon the retinal illumination must be less than one per cent. to be negligible, we may solve the equation: $d^2/(d - x)^2 - 1 = 1/100$ to determine how small x must be made in order that its influence can safely be neglected. We find: $x = d/201.5$, or the distance between the nodal point of the eye and the artificial pupil must be less than 1/200th of the distance between the nodal point

[1] See Cobb, *Psychol. Rev.*, 1916, 23, 80-81. This proof does not hold accurately for objects close to the eye, since the area of the retinal image depends on the distance from the object to the nodal point of the eye, while the total flux of light contributing to the illumination of the image depends on its distance from a plane between the iris and the cornea, the nodal point of the 'reduced eye' lying posterior to the iris.

and the stimulus surface in order that its influence shall be negligible. Accordingly, it is necessary to adopt some standard position for the pupil. Optically, the natural position would be at the nodal point of the eye, since if the pupil were at this point, the retinal illumination would be independent of the distance of the stimulus surface. However, the natural pupil ordinarily lies about 2.7 mm. anterior to the nodal point and an artificial pupil can hardly be placed nearer than 10 mm. to it, or about 4 mm. from the cornea.

On account of the general necessity for correction—whatever the standard position adopted—it seems advisable to choose the plane of the nodal point of the eye, although no pupil ever does actually take this position. On this basis, the photon value is given with considerable accuracy by the equation:

$$i = \frac{pbd^2}{(d - x)^2} \cos \phi, \tag{5}$$

the significance of the variables being as already defined.

Of course, the above discussion must be considered only as approximative, but formula (5) will suffice for most purposes.

The following formal definition may be given of the *photon*, and of *the physiological intensity of a visual stimulus*. A *photon* is that intensity of illumination upon the retina of the eye which accompanies the direct fixation, with adequate accommodation, of a stimulus of small area, the photometric brightness of which, as determined by the standard flicker comparison and a normal subject, is one candle per square meter, when the area of the externally effective pupil, considered as lying in the nodal plane of the eye, is one square millimeter. The *physiological intensity of a visual stimulus* is its intensity expressed in photons. The photon is a unit of illumination, and hence has an absolute value in meter-candles.[1]

[1] The numerical magnitude of the photon, in meter-candles, and also its reduction to energy units will be considered by the writer in a further paper. It will obviously be subject to some variation from individual to individual.

V. Summary

The present paper is a somewhat discursive study of certain very general questions with regard to the measurement of the intensity of visual stimuli. The writer hopes that as a review of facts, as well as of problems, the paper will prove itself useful to the psychologist.

The various meanings of the term intensity are discussed, and the fundamental significance of photometric and radiometric measurements is considered, together with the relations which hold between radiant energy and light. Recent important empirical studies of these questions are summarized. On the basis of these facts and a theory as to the probable physiological significance of photometric equations, it is claimed that in general such equations will be more useful to the student of visual psycho-physiology than will radiometric equations.

The fundamental presuppositions of a method of photometry are then taken under consideration, and on the basis of recent very careful studies of the method of flicker, it is claimed that this method should be adopted, at least tentatively, as the standard photometric procedure, whenever two compared lights show a color difference.

A third aspect of the problem concerns the influence of pupillary size and other factors besides the external brightness of the stimulus, upon the illumination of the retinal image. In a preliminary discussion of this question, new considerations with reference to the use of the artificial pupil are presented, and the *photon*, defined as a unit of *physiological stimulus intensity*, is offered as a basis for the general standardization of conditions of visual experimentation, with regard to intensity.

This paper is written primarily for the experimental psychologist, rather than for the photometrician or illuminating engineer, but at the same time discusses fundamental problems of general interest.

March 29, 1916

A NEW METHOD FOR MEASURING REACTION-TIME

BY F. E. AUSTIN

Hanover, N. H.

The methods commonly adopted for measuring reaction-time, depend upon the use of an electromagnet operating some form of armature to which is attached a marker or stylus.

As is well known, every electromagnet has a reaction time of its own; that is, a certain interval of time elapses between the 'making' of the electrical connections closing the circuit, and the acting of the recording stylus. An interval of time also elapses between the 'breaking' of a circuit and the release action of an electromagnetic stylus arrangement.

Were the 'making' and the 'breaking' reaction times of a given electromagnetic stylus arrangement, of exactly the same duration, the apparatus could be relied upon to give consistent results. When, however, the lapse of time for the closing action is less than for the opening action an error is introduced in the record made by the apparatus.

Experiment seems to demonstrate that not only are electromagnet reaction times at make and break different, but that there is a considerable *variation* in the reaction time at make, for the same electromagnetic arrangement. This fact at once makes evident the introduction of a *variable* error in the results of many investigations not at all amenable to correction.

Were the variable error not a large one as compared with the quantities measured, its existence might be tolerated; the variable error has been found to be very large in proportion to such intervals as the shortest reaction times of individuals, and has led to the development of the new method designed to eliminate errors.

The method for measuring reaction time to be described is based upon the fact that the arc produced by an alternating

current between two electrodes is set up and extinguished twice during each cycle of alternations and also upon the accuracy with which the frequency of an alternating current may be indicated and observed by employing a so-called Frahm frequency meter.

If the image of an alternating arc be focused upon a photographic plate, and the plate be *exposed* while it is rapidly moved laterally in the focal plane, the impressions upon the plate when properly developed are as shown in Fig. 1; which

FIG. 1

shows two records made upon a moving film, by an arc produced between two ordinary electric-light carbons, by a so-called 60-cycle alternating current. It may be noted that the more rapid the motion of the film, the longer are the impressions or the dashes made by the light, and likewise the greater the distance between the light dashes.

A record produced by a 60-cycle alternating-current arc during one second would consist of 120 light dashes and a corresponding number of intervening spaces. Two dashes and two spaces would therefore occupy $\frac{1}{60}$ of the complete record for one second.

If a film should be moved at the rate of 60 inches per second, then 1 inch of record would correspond to $\frac{1}{60}$ of one second; which expressed as a decimal is $.016\frac{2}{3}$ second. By properly measuring the fractional part of one inch of such a record, less than $\frac{1}{60}$ of one second may be easily measured. For example $\frac{1}{4}$ inch of record as designated, would represent $\frac{1}{4}$ of $\frac{1}{60}$ or $\frac{1}{240}$ of one second; or expressed as a decimal $.004\frac{1}{6}$ second.

Should the film be moved at the rate of 120 inches or 10 feet per second, $\frac{1}{4}$ inch of record would represent $\frac{1}{480}$ of one second; or $\frac{1}{8}$ of an inch of record would represent $\frac{1}{960}$ of one second; or very nearly one one-thousandth of a second.

It is evident that the speed of the photographic film need not have a fixed constant value, but may vary considerably,

provided the *frequency* of the alternating arc *is known when any given record is produced* on the film. In other words the accuracy of record does not depend upon uniformity of motion of the surface upon which the record is made.

A frequency meter, such as the Frahm, consisting of carefully calibrated reeds is a very accurate indicator of frequency, and the essential requisite is to note the indication of the meter at the instant the sensitive film is exposed to the action of the light from the alternating arc.

To eliminate observational errors, a photograph (by flash-light if desirable) of the dial of the frequency meter can be taken *simultaneously* with the record on the moving film, but for ordinary investigations, a careful observer is sufficient.

Fig. 2 shows, in plan, the arrangement of apparatus used in obtaining reaction time for sight.

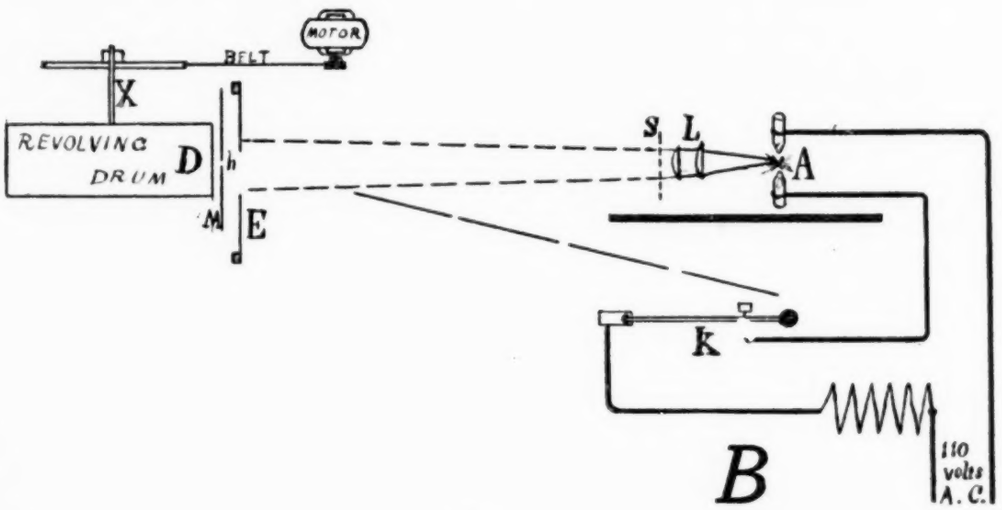


FIG. 2

The apparatus consists of an alternating-current arc *A*, a lens *L* to focus the beam of light from the arc upon the surface of a sensitive photographic film attached to the surface of a drum *D* that is arranged to revolve about an axis *X*. The drum is made of aluminum, is 6 inches wide and has a circumference of $45\frac{1}{2}$ inches; this means that a sensitive film $45\frac{1}{2}$ inches long and up to 6 inches wide may be used.

The dotted line at *S* represents a piece of any opaque

material such as a piece of thin board, that may be placed in front of the lens *L* in order to prevent the beam of light from striking the sensitive film. At *K* is located a key (shown in detail in Fig. 3) to be operated by the subject whose

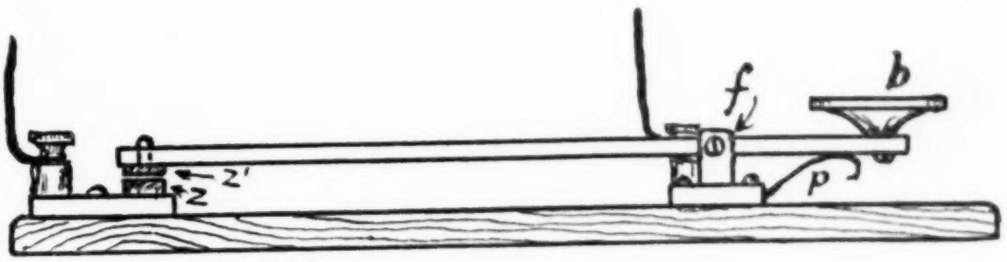


FIG. 3

reaction time is desired. By depressing the key the circuit is instantly opened and the arc extinguished. In order that the circuit may be quickly opened, the key is made as a lever with its longer arm on the opposite side of the fulcrum *f* (see Fig. 3) from the button *b* which the subject presses.

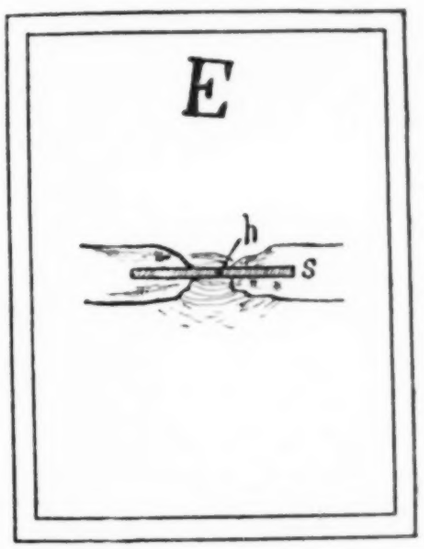


FIG. 4

A slight motion of the button *b* results in a motion at the break end of the arm, four or five times as great as at the button end, thus ensuring a very rapid opening of the circuit. The contacts *Z*, *Z'*, at the break, are small zinc plugs that may be easily removed and replaced as desired.

The screen at *E* (shown in elevation in Fig. 4) has a good

reflecting surface such as white cardboard, and a small slit *s* that allows a portion of the beam from the arc light to pass through a small round hole, *h*, in a movable slider and thence onto the surface of the moving film. The round hole in this slider shields all but a very narrow strip of film from exposure, and allows as many as 70 or 80 records on a film 5 inches wide; the diameter of the hole in the slider being only $\frac{1}{16}$ of an inch in diameter. The hole could be $\frac{1}{32}$ or even $\frac{1}{64}$ in diameter if desired, allowing two or three times as many records on a single film.

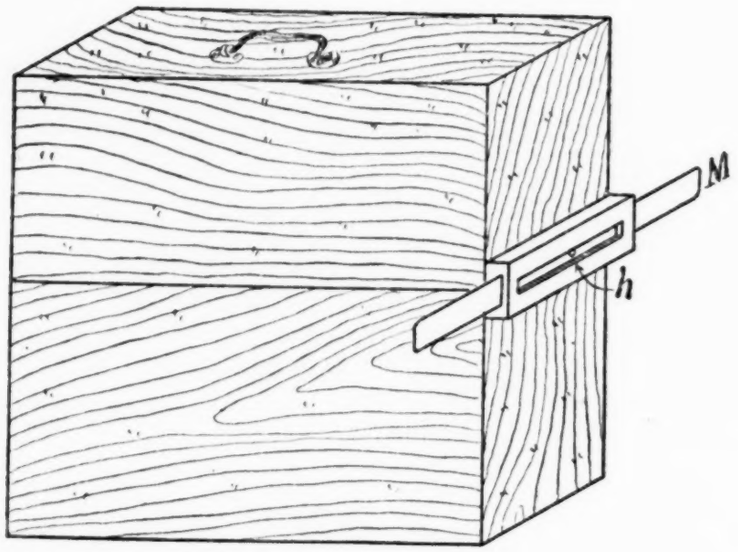


FIG. 5

Fig. 5 shows the wooden case covering the drum, with the movable slider *M* in which is the small hole; shown at *h*. The drum is rotated by means of a $\frac{1}{16}$ horse-power induction motor, properly belted to give the desired speed to the drum. The speed of the drum in making reaction-time records is about one revolution per second.

The experiment for obtaining the reaction-time for sight is performed as follows:

The subject, located at *B*, has the fingers of his hand on the key at *b*, and is told to depress the key as quickly as possible after seeing the image of the arc appear on the screen *E*.

When the opaque screen or shutter *S* is suddenly removed, the image of the arc flashes upon the screen *E* covering a considerable portion of the screen, while a small portion of the light passes through the slit in the screen and the small hole *h* in the slide *M* onto the rapidly moving film. As soon as the subject depresses the key after perceiving the image of the arc, the arc is extinguished and the record on the moving film ceases. The interval of time between the appearance of the image on the screen and the discontinuance of the arc, is the reaction-time of the individual, for sight.

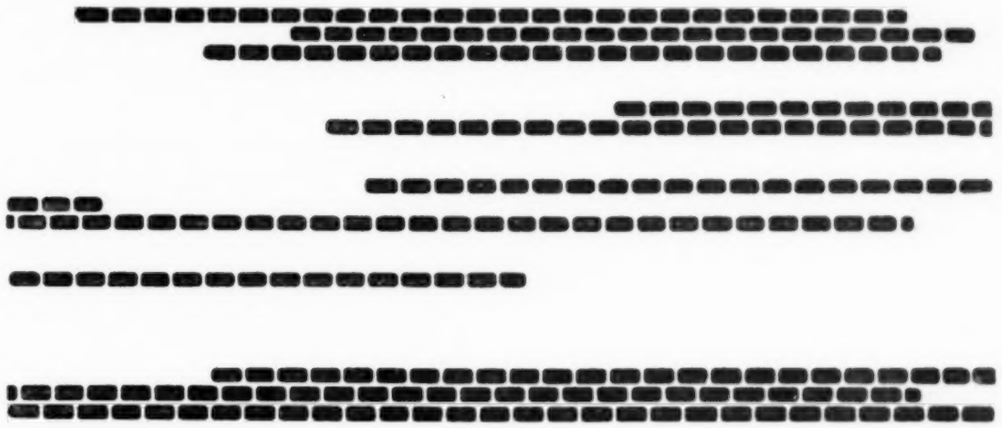


FIG. 6

The shutter *S* is then replaced, the arc again started, by bringing the carbons into momentary contact and then slightly separating them, the slide *M* moved along the width of the hole *h*, and the experiment repeated.

After sufficient records have been made to occupy the width of the film, and the film is removed and developed, blue prints may be made for purposes of reference and computations.

Records are evaluated by counting the number of complete dashes and measuring the fraction of a dash. The indication of the frequency meter is noted for the time each record is made. For accurate results the records should be made in a carefully noted sequence, numbered from a certain side of the film, and the direction of the motion of the film noted.

The method lends itself to class study, since any number

of blue prints may be made and distributed for individual computation and study.

It may be noted that the record is made by a *massless* index, a beam of light that travels about 188,000 miles in a second; that is about 992,640,000 *feet* per second. Since the arc at *A* is only three or four feet from the film, the time required to reach the film after the shutter *S* is removed is about 1/248,160,000 of a second; which is small when compared to the actual interval of reaction-time; this being from $\frac{1}{10}$ to $\frac{1}{5}$ of a second.

When the key opens the circuit the current ceases very quickly; whether or not the time of discontinuance of the circuit is of the same order as the velocity of light, it is very small in comparison with the quantity measured.

Fig. 6 is a reproduction from a blue print, of a section of a film obtained from experiment, showing several complete records, using a 60-cycle arc.

VISUAL DISCRIMINATION OF RECTANGULAR AREAS ILLUMINATED BY VARYING DEGREES OF ACHROMATIC LIGHT[1]

BY G. F. ARPS

Ohio State University

The primary purpose of this study is to determine the discriminative efficiency in the perception of areal differences and to analyze the various factors involved in the judgments.

Two series of experiments were made. None of the data for the first series is incorporated in this study, except three graphs, for the reason that as the experiment progressed it became more and more evident that discriminative efficiency, for the illuminations here investigated, is not a simple function of the illuminations. The rejected data (4,212 judgments) comprise one third of the total number of judgments given by all observers.

Means and Methods

The apparatus consists essentially of a light-tight box, a modified form of memory apparatus, tachistoscope, and a contact seconds pendulum which controls the magnet of the tachistoscope.

The entire apparatus is articulated by three independent circuits (Fig. 1): One alternating circuit, A. C., which provides light for the lamp on the trolley in the light box; one direct current, D. C. P., which enervates the pendulum and makes and breaks a second direct current, D. C. T., which enervates the tachistoscope. By means of a double-knife switch, S, the light in the box is switched off and on

[1] A paper presented before the American Psychological Association at the Chicago Meeting, December, 1915. I am indebted to Mr. C. M. Bock, fellow in the department, for his untiring work as experimenter and for the tabulation of the data. Acknowledgment is made to Kenneth Cottingham for preliminary experimentation and for construction of much of the apparatus.

by a partial depression of the knife; by a complete depression, the tachistoscope is set in function.

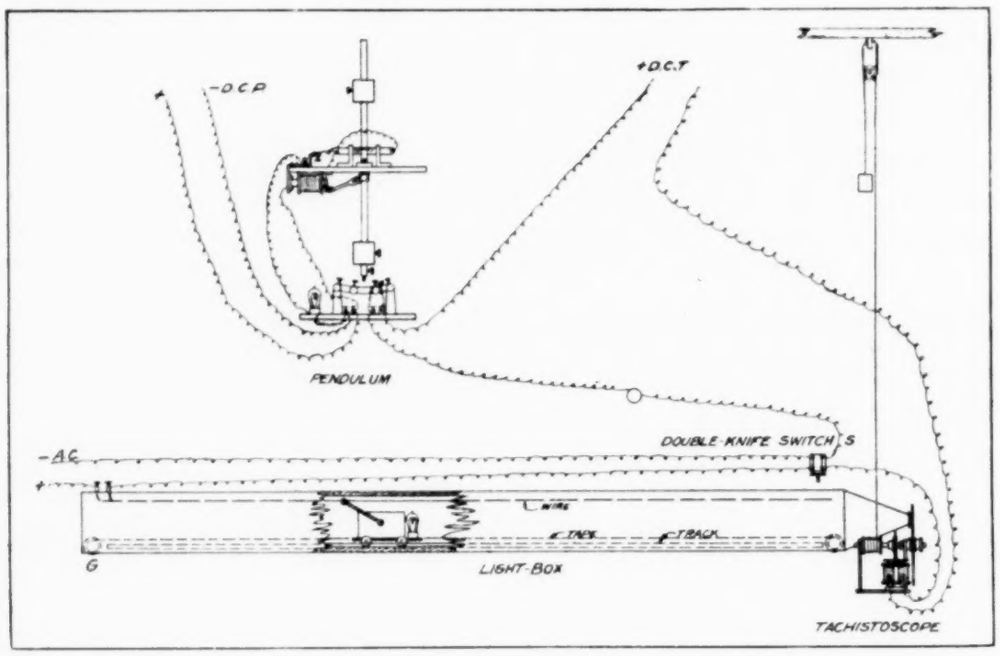


FIG. 1.
Diagram of Apparatus and Electrical Connections.

The box is 14 feet long, 16 inches high, by 12 inches wide, the inside of which is painted black. Within the box is the light carriage, mounted on flanged wheels running the length of the box upon a pair of rails. The light carriage is moved to different distances, depending upon the illumination desired, by a tape which runs, belt-like, through the box and beneath it, passing over a roller, G, at one end of the box.

One end of the box is covered with a tin truncated pyramid, the smaller end of which is pierced by an aperture covered by a piece of ground glass through which the light passes to the tachistoscopic slots. The tachistoscope consists of a circular disk, in whose periphery, placed at equal intervals, are twelve rectangular shaped apertures. Six of these apertures, or slots, are invariable in size and constitute the 'standard' stimulus. The remaining six slots are variable and are provided at one end with a slide by means of which the lengths of the rectangles can be varied at pleasure. These constitute the 'variable' stimuli and are presented

alternately with the standard, the time interval being two seconds. For a cut of the tachistoscope see FIG. 2.

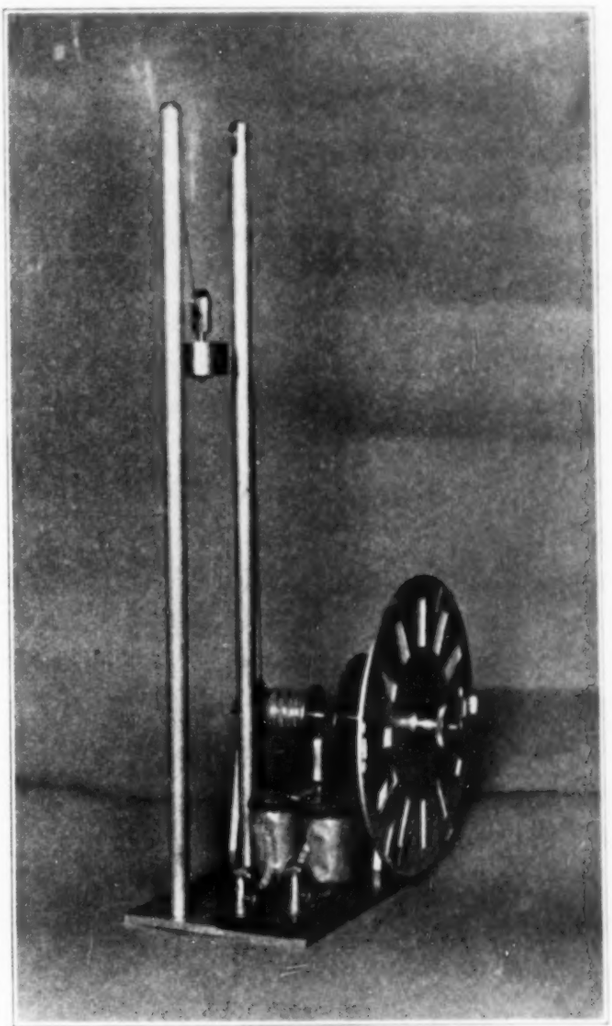


FIG. 2.

The six standard oblongs are exactly 40 mm. in length and 15 mm. in width; the remaining six vary as to length between the limits, lower and upper, of 38.50 and 41.50 millimeters, with steps of one quarter of a millimeter. In this way twelve variations, exclusive of the standard slot, are made possible.

In all, nine illuminations are employed as given in the graphs. An experiment consists in passing before the observer all of the twelve variables, each variable being pre-

ceded by a standard stimulus. An interval of two seconds separates the successive presentation of the standard and variable stimuli. Six judgments are given by each observer, on each variable for each illumination. A more detailed statement of the procedure is as follows: Of the twelve variables, six sizes are chosen by chance, and the oblongs equated on the disk accordingly, the order of the appearance of the oblongs on the disk again being left to chance. The disk is then rotated before the observer, in the manner explained above, and a judgment required on each variable as it appears. The remaining six sizes are now selected and equated as the first six, and similarly used. The division of the twelve variables into two sets, of six each, is made necessary for the reason that the disk was not large enough to contain all the variables and standards at one time.

Following essentially the procedure described for the variables, six judgments are made on the standards as to their variability. The total number of judgments beginning with the shortest or longest variable to, and including, the longest or shortest is, therefore, thirteen. All judgments are expressed as 'longer' (+), 'shorter' (−), or 'equal' (=).

Three observers function in the experiment, *A*, *B*, and *C*. One of the observers is an instructor in the department of psychology and two are graduate students of extended psychological training. The middle point of the illuminated areas is the most favorable fixation point and is maintained throughout.

The above procedure is carried out with the stimulus areas in four positions, viz., the horizontal, vertical and two intermediate positions in which the oblongs incline to the right or left of the vertical position at an angle of 45 degrees. The inclined positions are made possible by tilting the tachistoscope.

Results of the Experiments

(*a*) *Individual Efficiencies*

The important results are set forth, in sixteen graphs, four composite and twelve individual. One additional graph

shows the relative discriminative efficiency, the relative inefficiency and the relative mediocrity of the various illuminations.

The final efficiency value (limen) for each point on the individual graphs is obtained by taking the mean of the negative and positive limens. The negative limen, for example, is computed from a decreasing series of variable stimuli. When two thirds of the judgments on a variable, nearest the standard, are correct, the value of that variable represents the limen of discrimination. The positive values are similarly computed.

The final efficiency value for each individual graph on each illumination is derived from 78 judgments, 6 judgments on each of the 13 variables. The final efficiency value for each illumination on a composite graph for any one of the four positions investigated, therefore, represents a total of 234 judgments. Since there are four positions investigated, each illumination receives 936 judgments.

For the horizontal position, maximal and minimal discriminative efficiency is found at 5.86 and 8.20 c.p. respectively. For the vertical position, maximal efficiency shifts to 1.80 and 4.06 c.p. and minimal efficiency to .50, 1.06 and 2.29 c.p. For the diagonal positions, left and right of the vertical position, maximal efficiency is found between 1.06 and 1.80 c.p. and at 1.06 c.p. respectively, while minimal efficiency for the same positions lies between 2.29 and 8.20 c.p. and at 5.86 c.p. respectively.

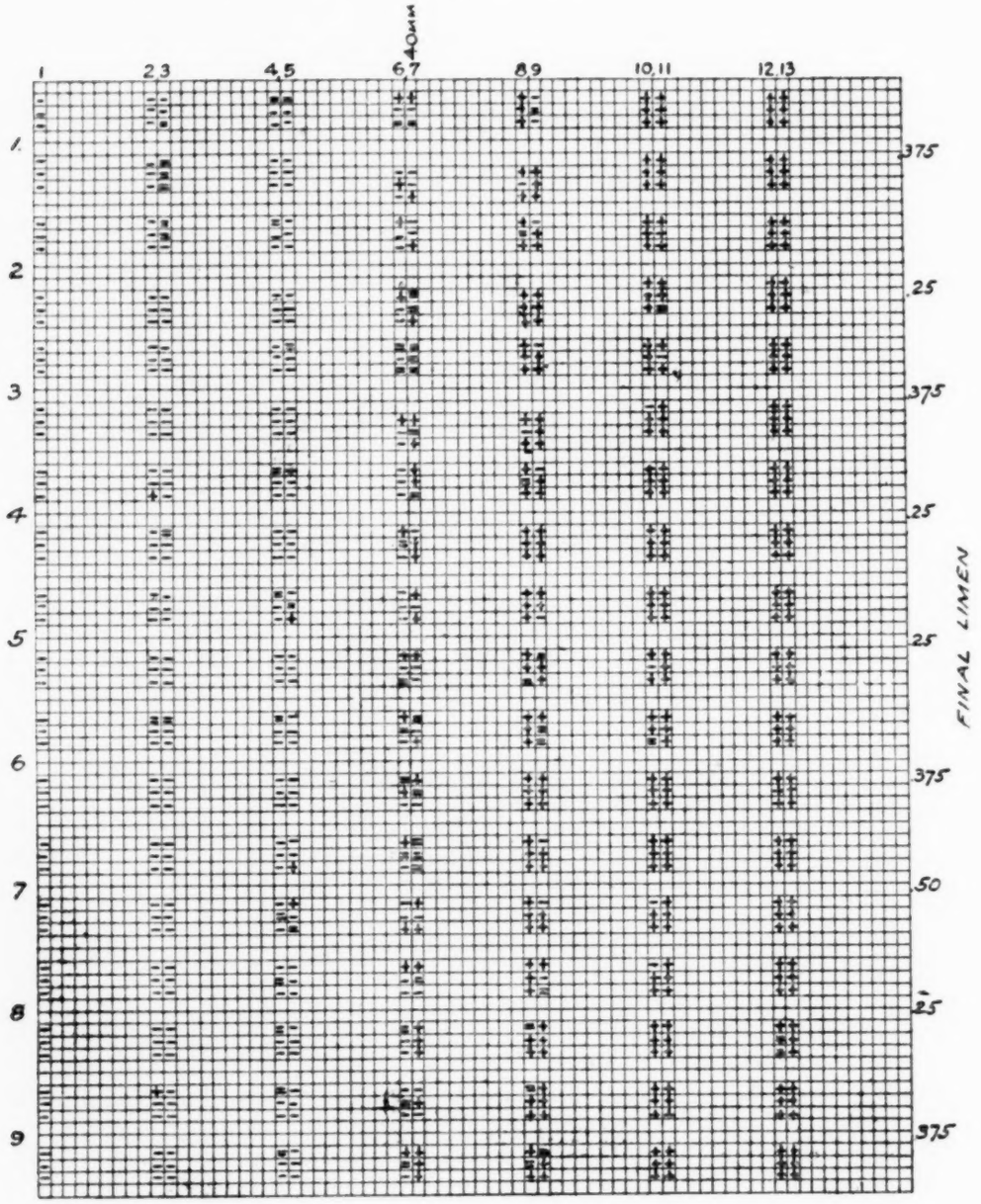
The greatest variations between the maximal and minimal discriminative efficiencies for each of the positions investigated as shown by the composite graphs are as follows: .15 mm. for the horizontal, .080 for the vertical, .20 for the left diagonal, and .080 for the right diagonal position.

Tables I., II. and III., corresponding to graphs II. '*A*,' III. '*B*' and IV. '*C*,' illustrate the distribution of judgments, the relation of the variables, and the negative, positive and final limens.

The character of the data lends itself readily to the computation of the relative efficiency, the relative inefficiency

TABLE I

OBSERVER "A" HORIZONTAL POSITION

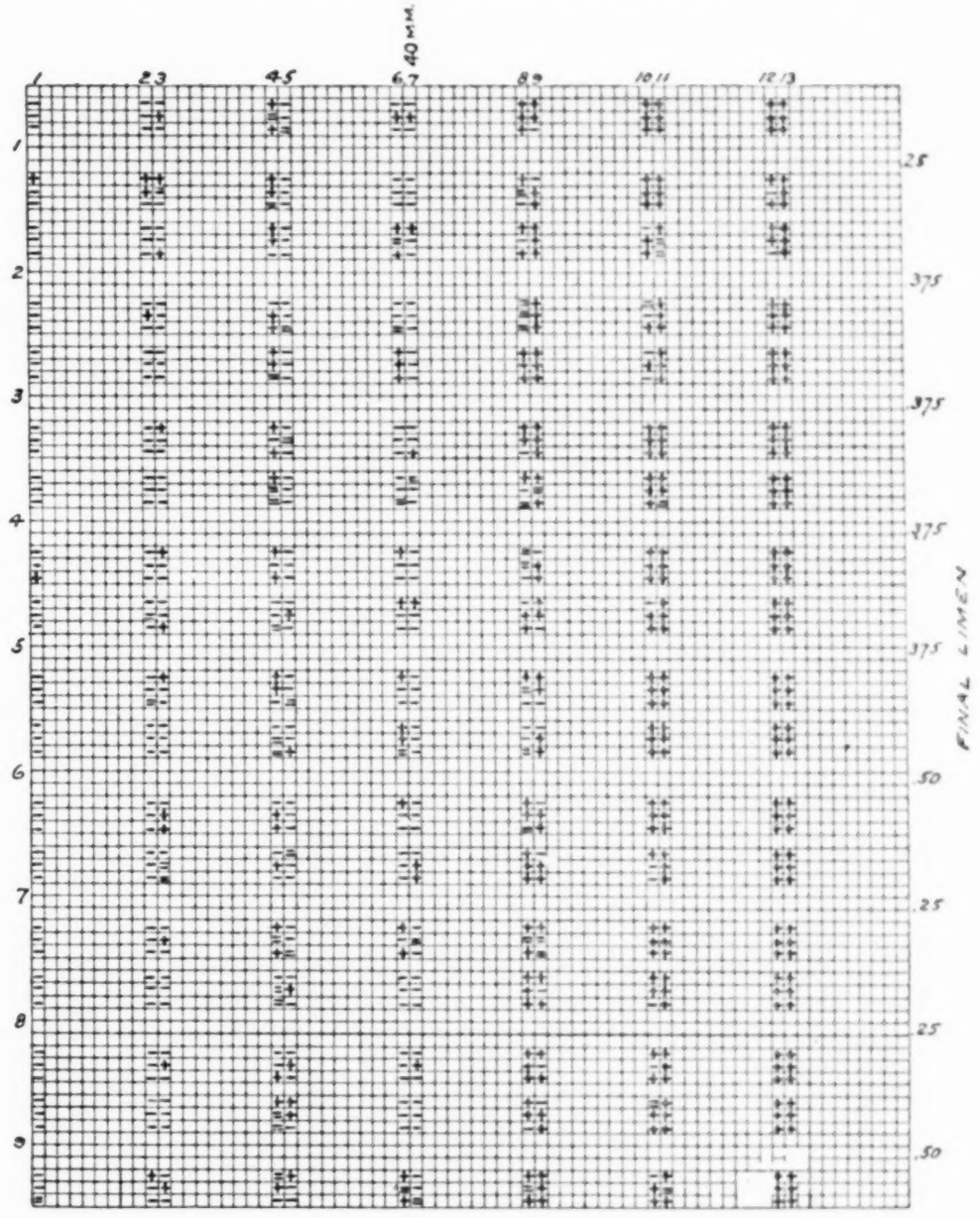


Numerals at the top, 1, 2, 3, etc. indicate the size of the variables, 38.50 mm., 38.75 mm., 39 m.m., etc.
" " " " left hand edge, 1, 2, 3, 4, etc. indicate the successive illuminations, .20, .50, 1.06 etc. c.p.

and the relative mediocrity of the various illuminations for all observers. It also lends itself readily to the computation of the relative efficiency of the observers themselves.

TABLE 2

OBSERVER "B". HORIZONTAL POSITION



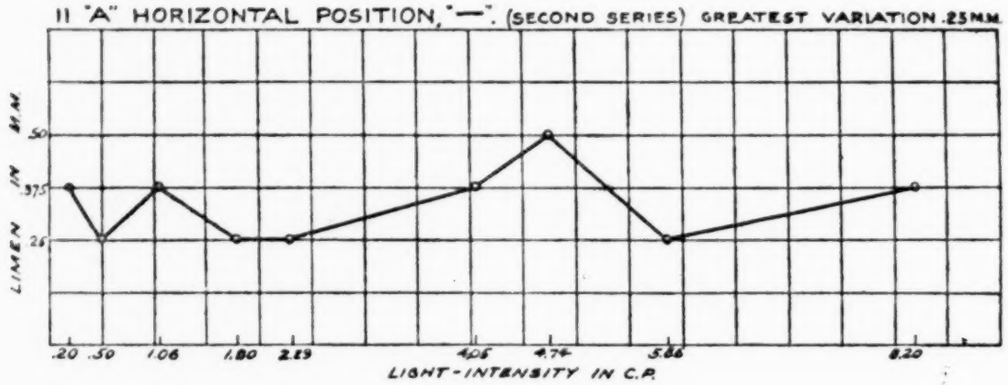
Numerals at the top, 1, 2, 3, etc. indicate the size of the variables, 38.50 mm, 38.75 mm, 39 mm. etc.

" " " " left hand edge, 1, 2, 3, 4, etc. indicate the successive illuminations, 20, 50, 106 cp. etc.

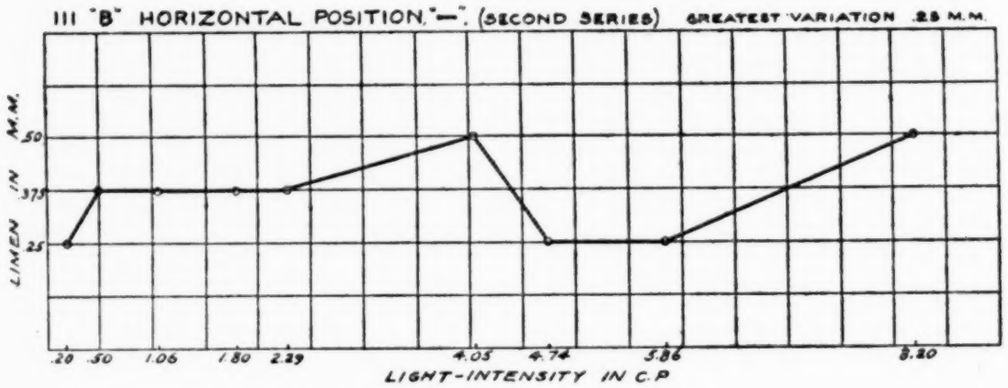
(*b*) *Relative Efficiency of the Illuminations*

The relative efficiency of the various illuminations is derived from a consideration of the low limen of these illuminations. The results show that the illumination of

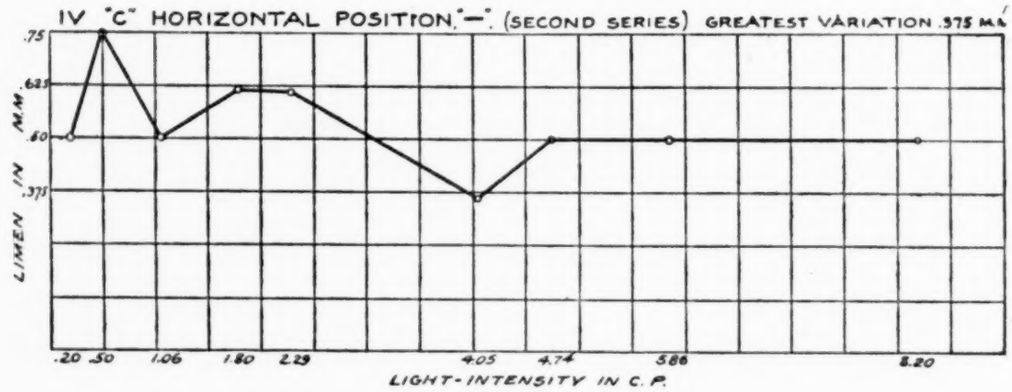
II "A" HORIZONTAL POSITION, "—". (SECOND SERIES) GREATEST VARIATION .25 M.M.



III "B" HORIZONTAL POSITION, "—". (SECOND SERIES) GREATEST VARIATION .25 M.M.



IV "C" HORIZONTAL POSITION, "—". (SECOND SERIES) GREATEST VARIATION .375 M.M.



I COMPOSITE HORIZONTAL POSITION, "—". (SECOND SERIES) GREATEST VARIATION .15 M.M.

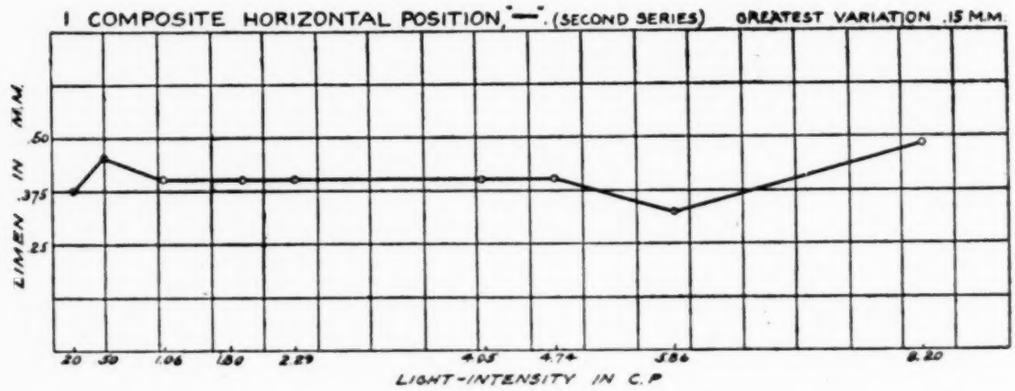
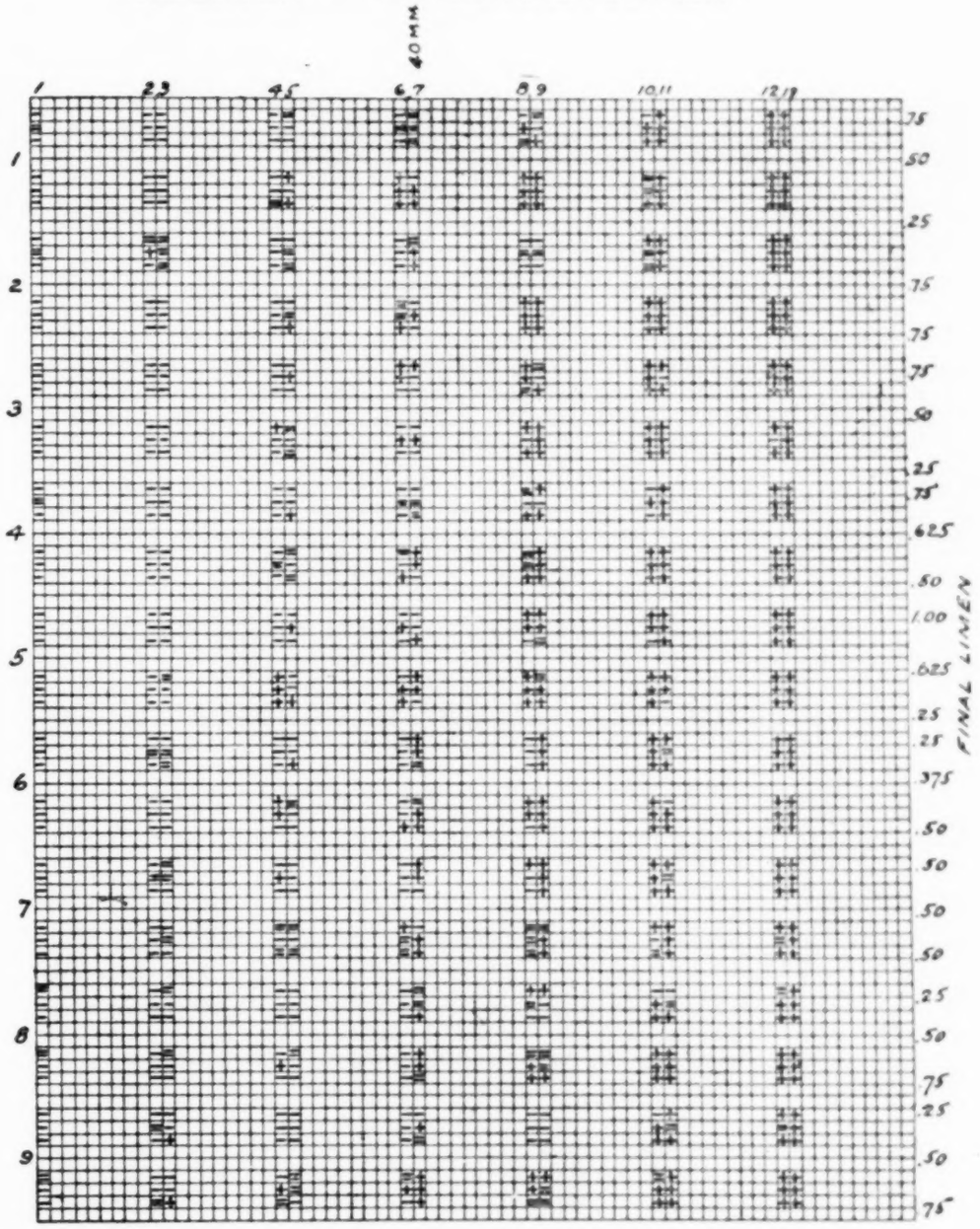


TABLE 3

OBSERVER "C" HORIZONTAL POSITION



Numerals at the top, 1, 2.3, etc. indicate the size of the variables, 38.50 m.m., 38.75 m.m. 39 m.m. etc.
" " " - left hand edge, 1, 2.3, 4, etc. indicate the successive illuminations, 2.0, 50, 1.06 c.p. etc.

1.06 c.p. has the highest relative efficiency value of all the illuminations, being 28 on a scale ranging from 1 to 30, while the illumination 2.29 c.p. has the lowest value, being 4 on the same scale.

Deriving now the relative *in*efficiency of the various illuminations through a consideration of the high limen we find that illuminations .50 and 4.74 c.p. are equally and

TABLE IV

RÉSUMÉ AND COMPARATIVE TABLES—OBSERVERS *A*, *B*, *C*

'Figures' are in 'thousands' of one millimeter, and indicate the average limen, as defined in this study.

From the columns *A*, *B*, *C*, are derived the credit values given under Table V.

	C. P.	*A*	*B*	*C*	Av.
'—'	.20	375	250	500	375
	.50	250	375	750	465
	1.06	375	375	500	416
	1.80	250	375	625	416
	2.29	250	375	625	416
	4.06	375	500	375	416
	4.74	500	250	500	416
	5.86	250	250	500	333
	8.20	375	500	500	486
					Average, 416
'/'	.20	500	375	500	458
	.50	625	500	250	458
	1.06	500	250	250	333
	1.80	625	375	250	420
	2.29	625	500	375	500
	4.06	500	500	375	458
	4.74	625	375	500	500
	5.86	625	500	500	540
	8.20	500	500	375	458
					Average, 458
'\'	.20	625	500	375	500
	.50	625	500	375	500
	1.06	500	375	500	458
	1.80	500	375	500	458
	2.29	625	500	500	542
	4.06	625	500	500	542
	4.74	625	500	500	542
	5.86	625	500	500	542
	8.20	625	500	500	542
					Average, 514
'|'	.20	375	500	250	375
	.50	500	500	250	413
	1.06	500	500	250	413
	1.80	375	375	250	333
	2.29	500	500	250	413
	4.06	375	375	250	333
	4.74	500	375	250	375
	5.86	500	375	250	375
	8.20	375	375	250	333
					Average, 373

most inefficient relatively, while illumination 1.80 c.p. is, relatively, least inefficient of all the illuminations.

Finally, if we consider the relative mediocrity of all the illuminations by a consideration of the average limen we find that illuminations .20 and .50 c.p. have the highest and lowest mediocre value respectively (Tables IV. and V.).

All the above relationships are set forth in three curves (Graph XVII.), derived from the data summarized in Table VI.

TABLE V

RELATIVE EFFICIENCY COEFFICIENTS OF VARIOUS ILLUMINATIONS FOR ALL OBSERVERS

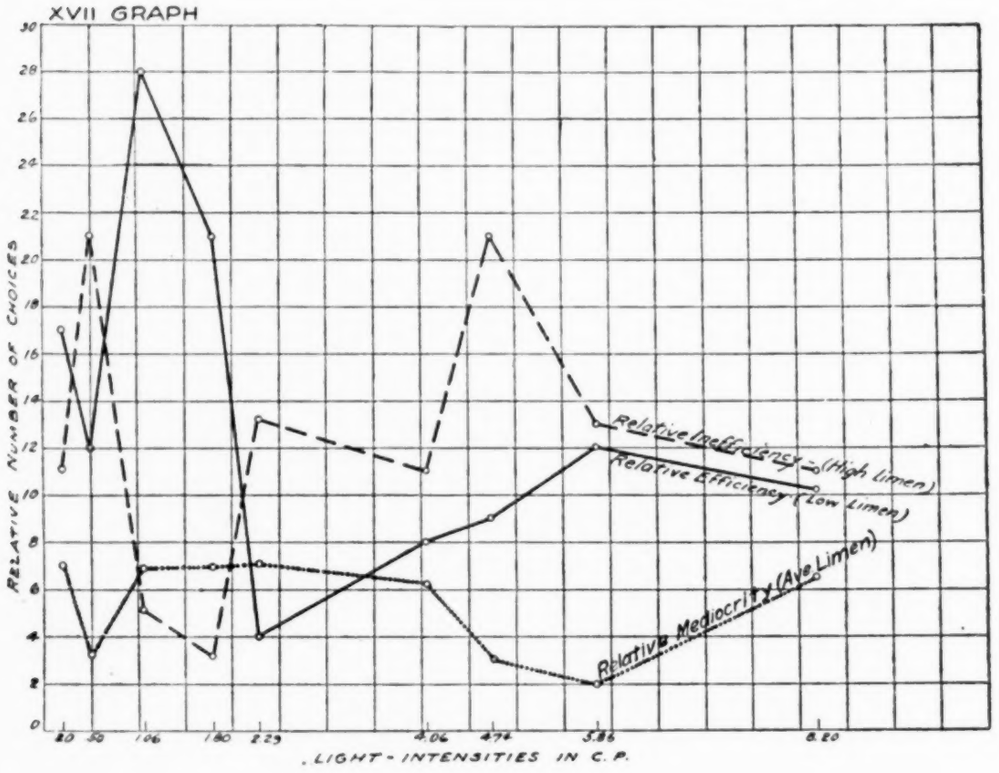
Illumination	—A	—B	—C	A—/	B—/	C—/	A—\	B—\	C—\	A—|	B—|	C—|	Total
.20		333	200	250					500	250		111	1.644
.50	250					333			500			111	1.194
1.06			200	250	1.000	333	500	500				111	2.894
1.80	250					333	500	500		250	200	111	2.144
Low limen, 2.29	250											111	.361
4.06				250						250	200	111	.811
4.74		333	200								200	111	.844
5.86	250	333	200								200	111	1.299
8.20			200	250						250	200	111	1.011
.20	250		140		333								.723
.50		250											.250
1.06	250	250	140										.640
1.80		250	140		333								.723
Av. limen, 2.29		250	140			333							.723
4.06	250					333							.583
4.74			140		333								.473
5.86			140										.140
8.20	250		140			333							.723
.20						333	140	140			250		1.063
.50			1.000	200	200		140	140		200	250		2.130
1.06									140	200	250		.590
1.80				200					140				.340
High limen, 2.29				200	200		140	140	140	200	250		1.270
4.06		500			200		140	140	140				1.120
4.74	1.000			200		333	140	140	140	200			2.153
5.86				200	200	333	140	140	140	200			1.353
8.20		500			200		140	140	140				1.120

Method.—For any position and any observer select that illumination which has the lowest limen; to this illumination, give one unit credit. Do this for all positions and all observers. Summate. These sums are the relative efficiency coefficient. In case two or more illuminations share the low limen, give each one half, etc., credit. For the derivation of the credit values given above see Table IV.

TABLE VI

SUMMARY OF TABLE V

Illumination	Gets Low Limen	Average Limen	High Limen
.20	1,644 times	723 times	1,063 times
.50	1,194 "	250 "	2,130 "
1.06	2,894 "	640 "	590 "
1.80	2,144 "	723 "	340 "
2.29	361 "	723 "	1,270 "
4.06	811 "	583 "	1,120 "
4.74	844 "	473 "	2,153 "
5.86	1,229 "	723 "	1,353 "
8.20	1,011 "	723 "	1,120 "



(c) *Relative Efficiency of the Observers*

To determine the relative efficiency of the observers, each observer was ranked in order of his limen for all illuminations of a given position. The observer having the lowest limen for any given illumination was graded '1'; the one having the highest limen was, therefore, graded '3.' A perfect score for any position would be represented by '9,' since there are 9 illuminations. For example, observer *A* for the horizontal position ranked '1' in 7 of the 9 illuminations

and '2' in 2 of them. If we divide the number of illuminations (9) by the sum of *A*'s ranks, which is 11, we get *A*'s relative efficiency for the horizontal position, which is 0.81. Now if we similarly rank observer *A* for the remaining positions and divide by the number of positions, we get *A*'s relative efficiency for all positions and all illuminations. In a similar manner compute the relative efficiencies of *B* and *C*. The results show that the relative efficiencies of observers *A*, *B*, and *C* are .51, .63, .76 respectively where unity represents perfect efficiency (Table VII.).

TABLE VII

COMPARATIVE TABLE OF OBSERVERS' EFFICIENCY

	Σ	$\frac{\Sigma}{\div 9}$	/	\	|	$\frac{\Sigma}{\div 4}$
Horizontal, '—,' Position:						
A 2, 1, 1, 1, 1, 1, 2, 1, 1	11	0.81	0.39	.410	.410	*.510*
B 1, 2, 1, 2, 2, 2, 1, 1, 2	14	0.63	0.63	.810	.460	*.630*
C 3, 3, 2, 3, 3, 1, 2, 2, 2	21	0.43	0.81	.810	1.000	*.760*
Diagonal, '/,' Position:						
A 2, 3, 2, 3, 3, 2, 3, 2, 3	23	0.39				
B 1, 2, 1, 2, 2, 2, 1, 1, 2	14	0.63				
C 2, 1, 1, 1, 1, 1, 2, 1, 1	11	0.81				
Diagonal, '\,' Position:						
A 3, 3, 3, 3, 2, 2, 2, 2, 2	22	0.41				
B 2, 2, 1, 1, 1, 1, 1, 1, 1	11	0.81				
C 1, 1, 2, 2, 1, 1, 1, 1, 1	11	0.81				
Vertical, '|,' Position:						
A 2, 2, 2, 2, 2, 2, 3, 3, 2	20	0.41				
B 3, 2, 2, 2, 2, 2, 2, 2, 2	19	0.460				
C 1, 1, 1, 1, 1, 1, 1, 1, 1	9	1.000				

Method.—Rank the observers in order of their limens, for all illuminations of a given position. Summate. Divide each such sum by '9,' since that would have been a perfect score, relatively, if any observer had stood first in all the illuminations. Do this for other positions, summate, and divide by '4' to get average for all positions.

(*d*) *Relative Efficiency of the Positions*

Of the four positions, the horizontal and vertical positions are equal in relative efficiency and both higher than the diagonal positions. The right slanting diagonal stands next in efficiency while the left slanting diagonal is least efficient. The numerical equivalents of the various positions are: .59,

.47, .41, .59 respectively for the horizontal, right diagonal, left diagonal and vertical. On the basis of normal eye usage we should expect the order of relative efficiency to follow

TABLE VIII

RÉSUMÉ AND COMPARATIVE TABLE SHOWING RELATIVE EFFICIENCY OF THE FOUR POSITIONS

Obs.	Limen in Thousands of a Mm.					Rank	Coefficient of Efficiency
	'—'	'/'	'\'	'|'			
A	375	500	625	375	.20	1, 2, 3, 1	
B	250	375	500	500	.20	1, 2, 3, 3	
C	500	500	375	250	.20	3, 3, 2, 1	
A	250	625	625	500	.50	1, 3, 3, 2	
B	375	500	500	500	.50	1, 2, 2, 2	
C	750	250	375	250	.50	3, 1, 2, 1	
A	375	500	500	500	1.06	1, 2, 2, 2	
B	375	250	375	500	1.06	2, 1, 2, 3	
C	500	250	500	250	1.06	2, 1, 2, 1	
A	250	625	500	375	1.80	1, 4, 3, 2	
B	375	375	375	375	1.80	1, 1, 1, 1	
C	625	250	500	250	1.80	3, 1, 2, 1	
A	250	625	625	500	2.29	1, 3, 3, 2	
B	375	500	500	500	2.29	1, 2, 2, 2	
C	625	375	500	250	2.29	4, 2, 3, 1	
A	375	500	625	375	4.06	1, 2, 3, 1	
B	500	500	500	375	4.06	2, 2, 2, 1	
C	375	375	500	250	4.06	3, 3, 2, 1	
A	500	625	625	500	4.74	1, 2, 2, 1	
B	250	375	500	375	4.74	1, 2, 3, 2	
C	500	500	500	250	4.74	2, 2, 2, 1	
A	250	625	625	500	5.86	1, 3, 3, 2	
B	250	500	500	375	5.86	1, 3, 3, 2	
C	500	500	500	250	5.86	2, 2, 2, 1	
A	375	500	625	375	8.20	1, 2, 3, 1	
B	500	500	500	375	8.20	2, 2, 2, 1	
C	500	375	500	250	8.20	3, 2, 3, 1	
Total '—'						46	.59 (27/46)
" '/'						57	.47 (27/57)
" '\'						65	.41 (27/65)
" '|'						40	.59 (27/40)

Method.—Give to that position, in the column marked 'Rank' a number, to indicate whether that position had the lowest, second lowest, etc., limen. Add the four vertical columns of figures. Divide 27 by each such sum since any position, had it had the lowest limen all the time, would have polled $27 \times 1 = 27$.

what we have found, with the exception that the vertical position should be next in efficiency to the horizontal but not equal to it (see Table VIII.).

Observations and Conclusions

An analysis of certain of the factors involved in the judgments of spacial differences of the areas here investigated yields some interesting results.

1. So far as could be determined, eye-movement appears to play no direct role in a judgment. The chief function of movement in the 'free' eye is to secure and maintain a position maximally favorable to adequate retinal stimulation. Conscious increment of eye-movement acts certainly as a distraction. Observer *A* says: "When I run my eyes over the oblong, horizontally and vertically, in order better to grasp the area, I lose all sense of security. At such times I frequently request the experimenter to repeat the series. On the other hand, inhibition of eye-movement, through fixation of the middle point of a rectangle, increases the sense of security and accuracy."

The chief criterion for a judgment in the case of observer *A* appears to be the total feeling of largeness or smallness of the compared areas, and this is true whether the rectangle as a whole (by fixating a middle point) or one of the lateral lines (by fixating the middle point of the line) is perceived. In confirmation of this fact several observations were made by fixating the middle point of one of the lateral lines. This 'total feeling' is correlated with the degree of simultaneous stimulation of retinal points. The kinæsthetic element due to eye-movement is not considered the primary criterion in the judgments of extents here investigated.

Observers *B* and *C* experience a peculiar feeling of 'thickening' or 'thinning' of a comparative oblong according to whether the judgment is 'longer' or 'shorter.' This illusion is an invariable criterion for a judgment and appears constant. Observer *C* says: "I get the feeling of size best when I maintain an unmoved attitude of completeness, when I take in the rectangle as a whole for then the illusory effect of 'thin-

ning' and 'thickening' is pronounced. I do better when I get a total impression of eye-stimulation."

2. The exact function of the standard stimulus in the judgment of a variable is difficult of definition. Observer *C* says: "When the variable is in the field I appear to judge it independently on its own merits, without the slightest back reference to the standard. I appear to have no after-image of the standard so as to make superposition possible." What lingering effects the standard stimulus may bring to the presence of the variable seems indissolubly merged with the latter. The judgment of a variable as 'longer' or 'shorter' rests apparently on the absolute value of the variable, and is immediately perceived as an expansion or shrinkage of the variable. Martin and Muller[1] and other investigators[2] in other fields have made similar observations.

3. During the entire period of experimentation all observers protested the real size of the standard area. Frequently at the close of a given series observer *A* gave it as his opinion that the normal sequence (standard followed by a variable) was not adhered to and that all of the judgments were consequently not made on the variable. Closer inquiry shows conclusively that the standard at times varied subjectively, that the same retinal impressions permitted of ambiguous interpretation. In this illusion the standard area altered its apparent size without a corresponding change in distance. This was, no doubt, true of the variables, but in such cases it was difficult of detection for the reason that a variable was expected to alter its size. Since the illusion is neither constant nor necessarily restricted to the standard area, it is apparent that such fluctuations have an important bearing on the accuracy of judgment. The partial control of this illusion and the reduction of the effects of practice may account for the almost horizontal appearance of the graphs. On the other hand, the inadvertent appearance of the illu-

[1] *Beitrage zur Analyse der Unterschiedsempfindlichkeit*, pp. 44–45.

[2] Arps, 'Introspective Analysis of Certain Tactual Phenomena,' *Psychological Review*, Vol. 19, pp. 345–346. Stumpf and Meyer, *Zeitschrift für Psychologie der Sinnesorgane*, Vol. 18, pp. 390–392.

sion may account for the different positions of the limens on the individual graphs.

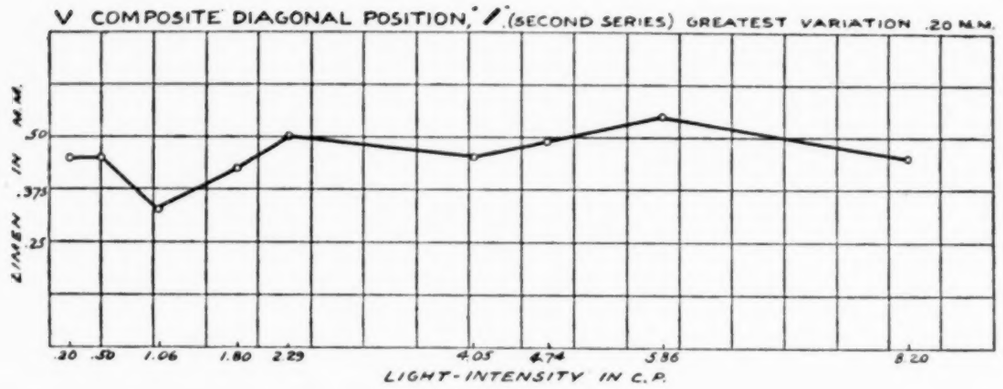
With reference to the illusion it should be added that when the fixation point is beyond the stimulus area we should expect double images of the area itself to appear. None of the observers, however, report the presence of such images.

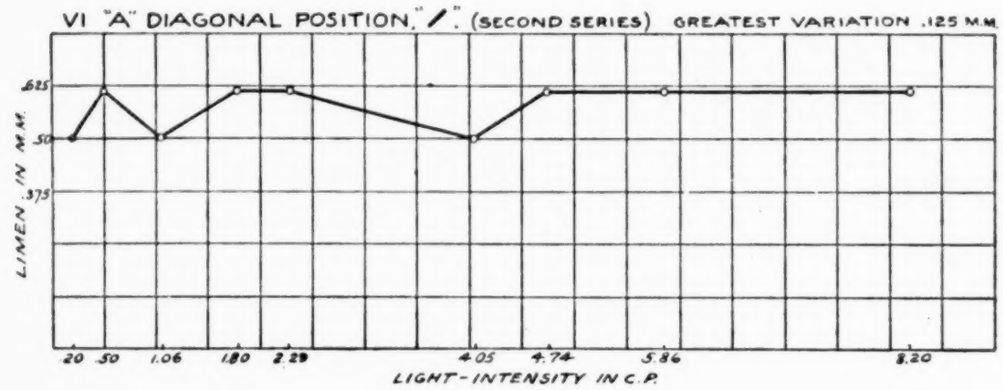
The explanation of the illusion is simple. Usually a change in size parallels a corresponding change in distance. Likewise a change in distance parallels a change in the optic axes. It is probable that we have here inadequate convergence and that the optic axes do not intersect at the stimulus area but beyond, so that the axes are more nearly parallel than is the case when the stimulus area is in focus. Thus the feeling of convergence is less intense than experience teaches is necessary to perceive the area as such a size and at such a distance. "If degree of convergence is a criterion for distance and if distance is a measure for the apparent size of an object then we have all the conditions necessary for an explanation of the illusion."[1]

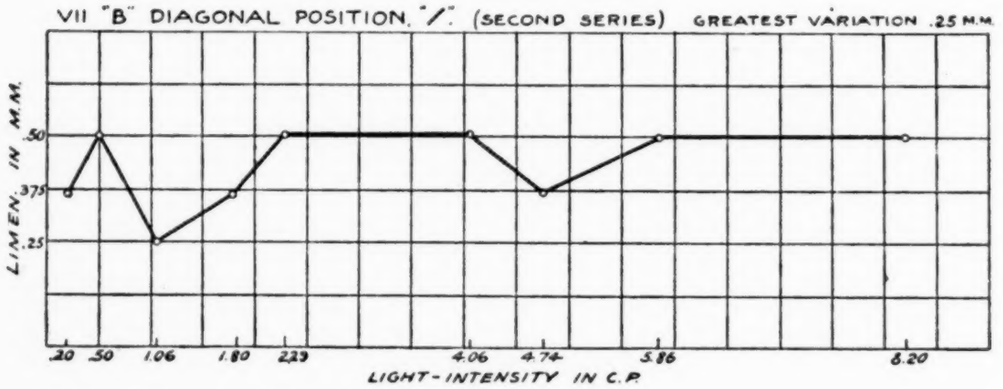
Connected with the apparent change in size of certain of the standard stimuli is the illusion of distance. Both observers *A* and *C* report that whenever the illusion of size is marked, the oblong appears to recede. Observer *A* says: "Whenever the standard varies decidedly, it seems more remote; at such times the succeeding variable fairly snaps into a nearer position."

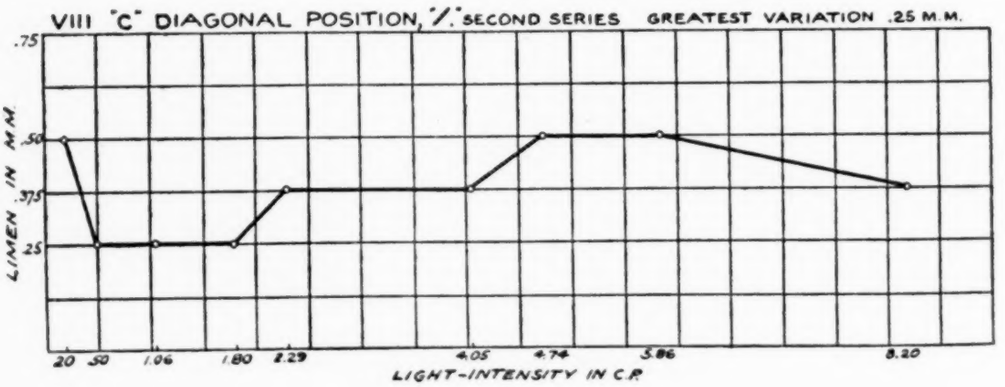
Here again the explanation is simple. Size and distance through innumerable repetition in experience, are linked into a permanent association, so that the one habitually becomes a sign for the other. A change in distance or size, therefore, is followed by the associated change in size or distance. For this reason an apparent decrease in the size of the standard oblong is supplemented by the idea of the oblong's greater distance. The two-dimensional space perception of the oblong is, consequently, enlarged into a tri-dimensional perception in the case of the standard oblongs with which the illusion of size is connected.

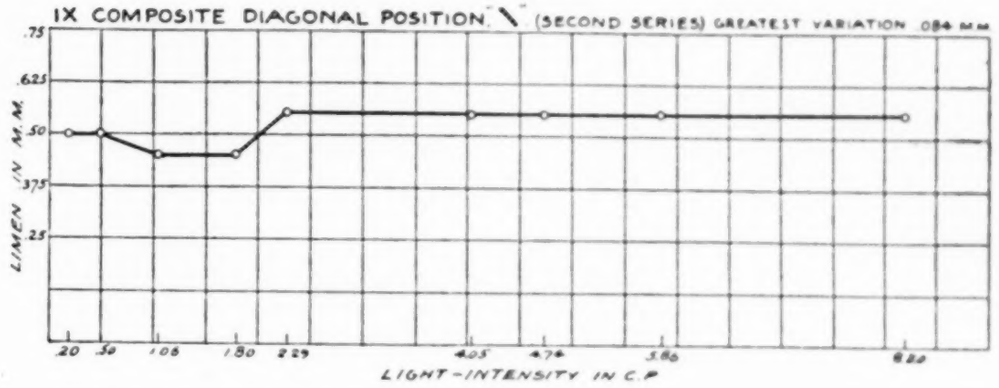
[1] Arps, 'Two Interesting Cases of Illusion of Perception,' *Journal of Abnormal Psychology*, Vol. X., pp. 211–212.

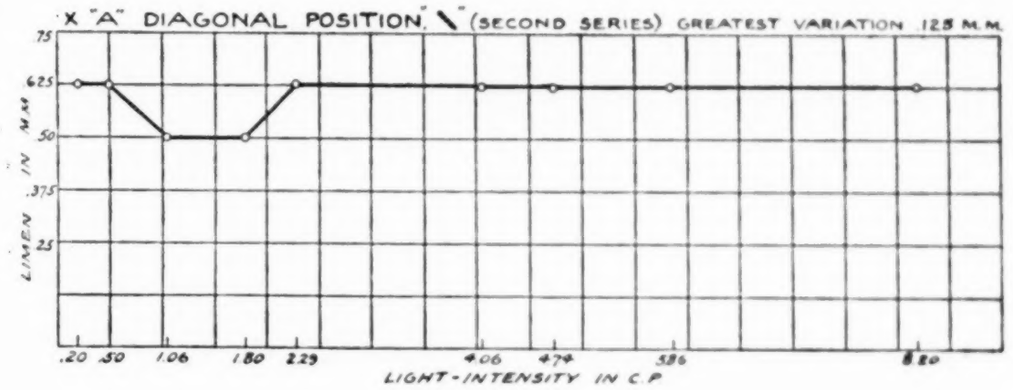

V COMPOSITE DIAGONAL POSITION, "/" (SECOND SERIES) GREATEST VARIATION .20 M.M.
LIMEN IN M.M.
.50
.375
.25
.20 .50 1.06 1.80 2.29 4.05 4.74 5.86 8.20
LIGHT-INTENSITY IN C.P.

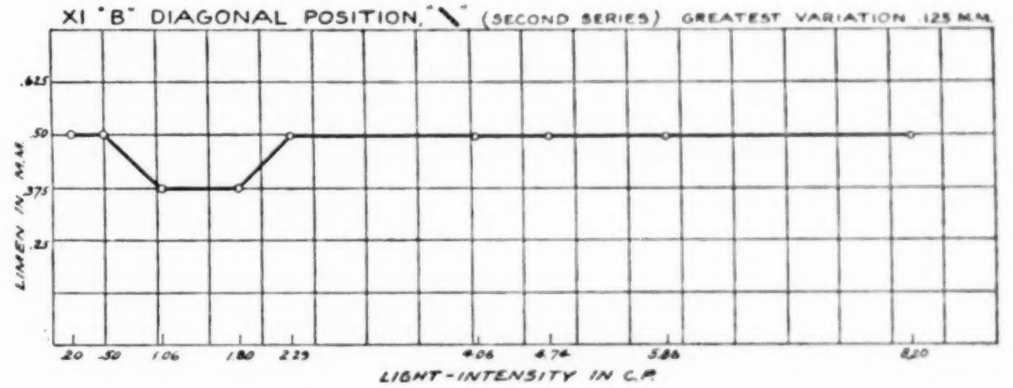

VI "A" DIAGONAL POSITION, "/". (SECOND SERIES) GREATEST VARIATION .125 M.M.
LIMEN IN M.M.
.625
.50
.375
.20 .50 1.06 1.80 2.29 4.05 4.74 5.86 8.20
LIGHT-INTENSITY IN C.P.

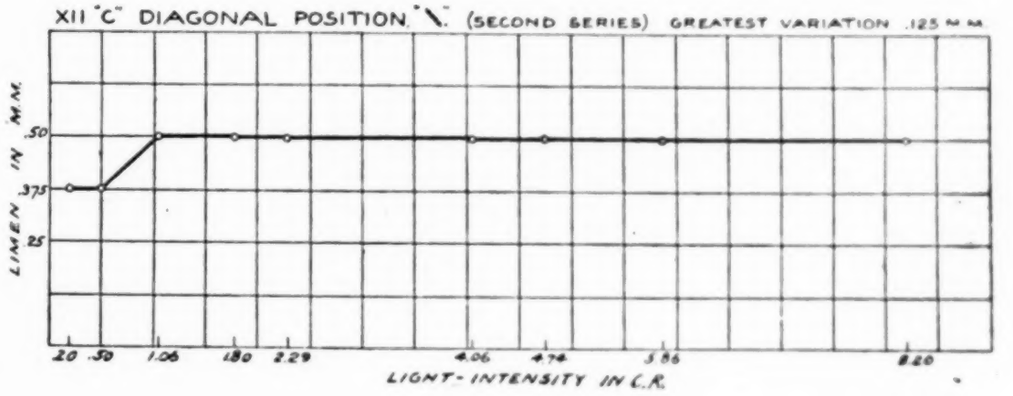

VII "B" DIAGONAL POSITION, "/". (SECOND SERIES) GREATEST VARIATION .25 M.M.
LIMEN IN M.M.
.50
.375
.25
.20 .50 1.06 1.80 2.29 4.06 4.74 5.86 8.20
LIGHT-INTENSITY IN C.P.

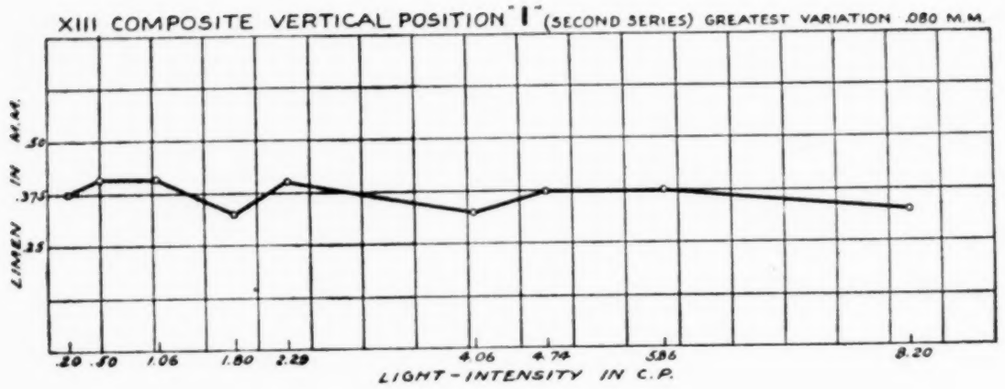

VIII "C" DIAGONAL POSITION, "/" SECOND SERIES GREATEST VARIATION .25 M.M.
LIMEN IN M.M.
.75
.50
.375
.25
.20 .50 1.06 1.80 2.29 4.05 4.74 5.86 8.20
LIGHT-INTENSITY IN C.P.

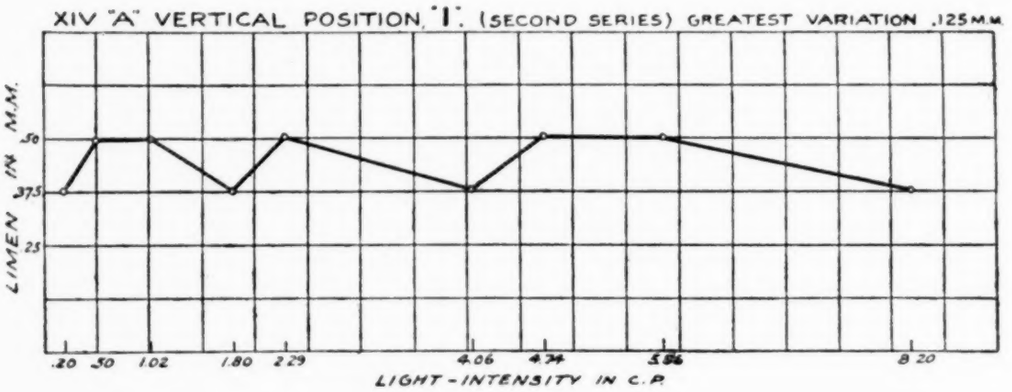

IX COMPOSITE DIAGONAL POSITION "\" (SECOND SERIES) GREATEST VARIATION .084 M.M.
LIMEN IN M.M.
.75
.625
.50
.375
.25
.20 .50 1.06 1.80 2.29 4.05 4.74 5.86 8.20
LIGHT-INTENSITY IN C.P.

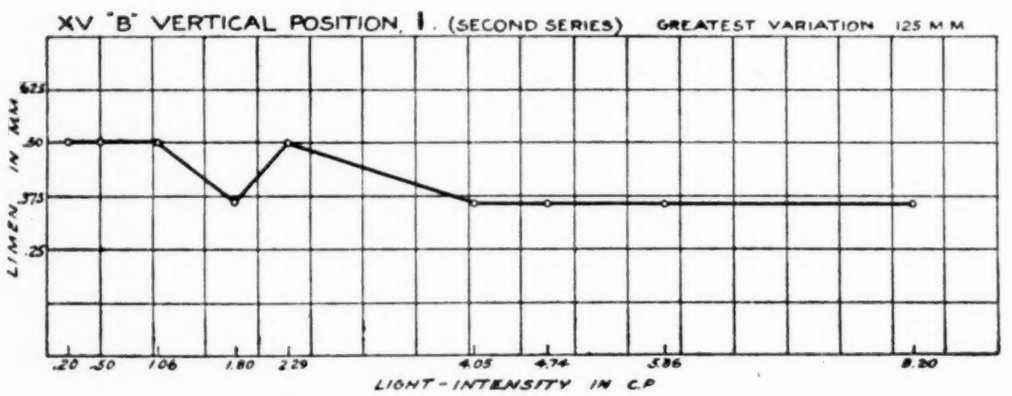

X "A" DIAGONAL POSITION "\" (SECOND SERIES) GREATEST VARIATION .125 M.M.
LIMEN IN M.M.
.75
.625
.50
.375
.25
.20 .50 1.06 1.80 2.29 4.06 4.74 5.86 8.20
LIGHT-INTENSITY IN C.P.

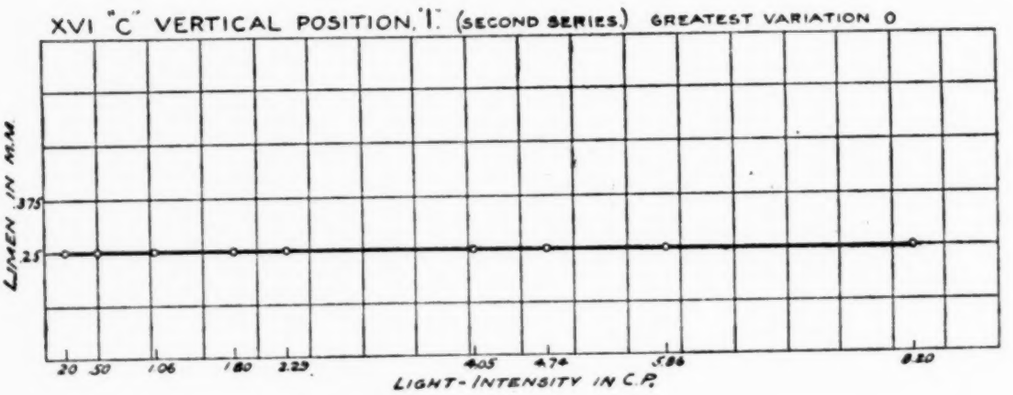

XI "B" DIAGONAL POSITION "\" (SECOND SERIES) GREATEST VARIATION .125 M.M.
LIMEN IN M.M.
.625
.50
.375
.25
.20 .50 1.06 1.80 2.29 4.06 4.74 5.86 8.20
LIGHT-INTENSITY IN C.P.


XII "C" DIAGONAL POSITION "\" (SECOND SERIES) GREATEST VARIATION .125 M.M.
LIMEN IN M.M.
.50
.375
.25
.20 .50 1.06 1.80 2.29 4.06 4.74 5.86 8.20
LIGHT-INTENSITY IN C.P.

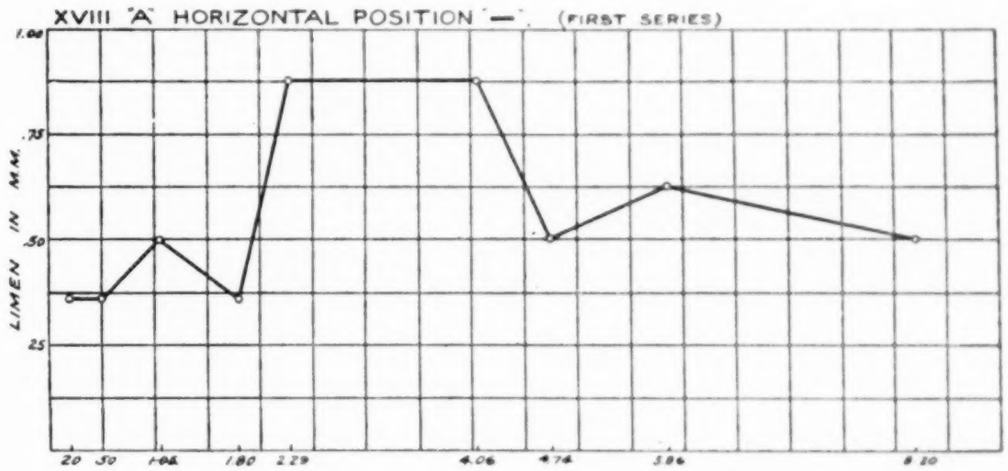

XIII COMPOSITE VERTICAL POSITION "I" (SECOND SERIES) GREATEST VARIATION .080 M M
LIMEN IN M.M.
.50
.375
.25
.20 .50 1.06 1.80 2.29 4.06 4.74 5.86 8.20
LIGHT-INTENSITY IN C.P.


XIV "A" VERTICAL POSITION, "I". (SECOND SERIES) GREATEST VARIATION .125 M M
LIMEN IN M.M.
.50
.375
.25
.20 .50 1.02 1.80 2.29 4.06 4.74 5.86 8.20
LIGHT-INTENSITY IN C.P.


XV "B" VERTICAL POSITION, I. (SECOND SERIES) GREATEST VARIATION 125 M M
LIMEN IN MM
.625
.50
.375
.25
.20 .50 1.06 1.80 2.29 4.05 4.74 5.86 8.20
LIGHT-INTENSITY IN C.P.


XVI "C" VERTICAL POSITION, "I". (SECOND SERIES.) GREATEST VARIATION 0
LIMEN IN M.M.
.375
.25
.20 .50 1.06 1.80 2.29 4.05 4.74 5.86 8.20
LIGHT-INTENSITY IN C.P.

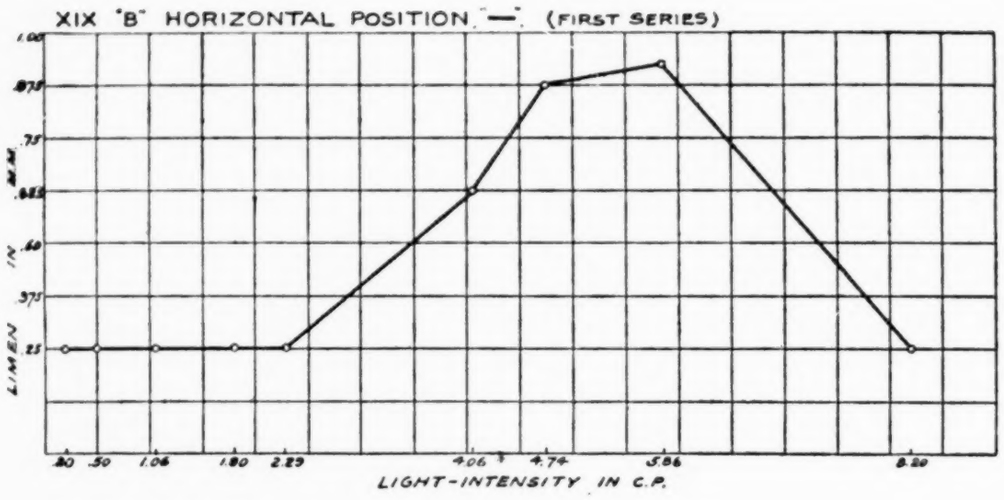
4. The graphs showing the relative efficiency, the relative inefficiency, the relative mediocrity of the illuminations and the individual and composite graphs seem to show that the limen is not a simple function of the illumination, for then we would expect a curve with a final efficiency maximum, *i. e.*, we would expect one illumination to have the greatest efficiency for all observers.

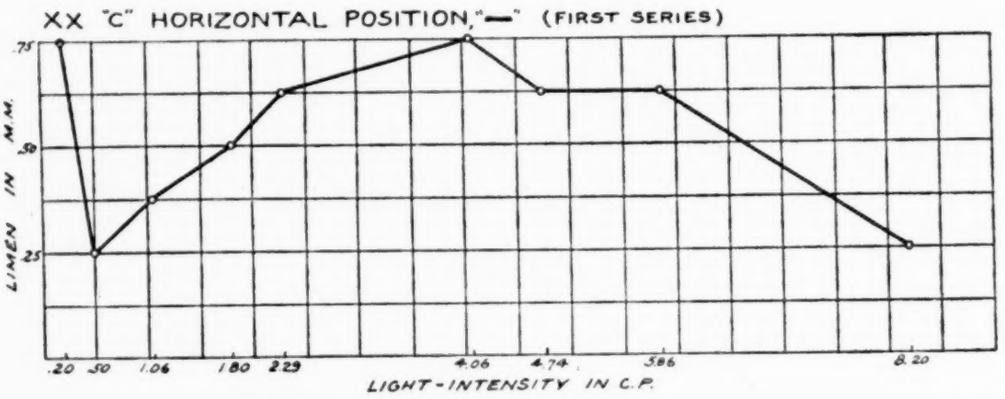


In case the illumination at the lowest limit were reduced in intensity to the point of bare perceptibility, and, at the highest limit increased to a disagreeable, or, even painful degree, we would expect very high limens at these two extremes of illumination. Convincing evidence on this point must be left, of course, for future experimentation.

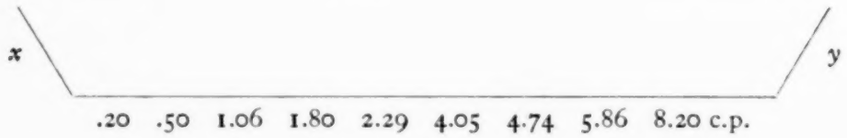
When we compare the graphs XVIII. '*A*,' XIX. '*B*' and XX. '*C*' of the first series of experiments with those of the second series, the general ironing out process due to practice is obvious. It is altogether likely that discriminative efficiency which determines the character of the graphs of the second series of experiments *is a simple function of habit.* It is not unlikely that the individual graphs would assume a straight line if it were possible to eliminate the illusion mentioned above, and certain unavoidable errors as may be due, for example, to bodily conditions. The efficiency of observer *C* for the vertical position (Graph XVI. '*C*') seems to substantiate this conclusion.

Taking observer *C*'s efficiency for the vertical position





and assuming high limens for the hypothetical illuminations at the extremes of the series of illuminations, we get the following diagrammatic graph:



It is altogether likely that the relation of the optimal stimuli (.20 c.p. . . . 8.20 c.p.) to the extreme stimuli (*x* and *y*) of this series would be typical of the relation existing between the multitudinous visual stimuli of normal life in which the extremes of the artificial series approximately correspond to growing darkness and brilliant sunlight.

Note.—It is desirable to continue the experiment and reduce the differential steps of the variable below .25 mm. The withdrawal of two of the observers, however, makes this impossible, and obviously new recruits can not begin where practiced observers end. Moreover, it is doubtful whether the main conclusions would be affected by the additional data.

AUDITORY ILLUSIONS OF MOVEMENT— A PRELIMINARY STUDY

BY HAROLD E. BURTT

Harvard University

Introduction

The following study was suggested by the experiments of Wertheimer[1] and Korte[2] on visual illusions of movement and of Benussi[3] on similar tactual illusions.

Wertheimer exposed in quick succession two parallel lines a few centimeters apart. Under certain conditions of time and distance it was possible to produce the impression of a line moving in the same direction as the actual temporal succession of the stimuli (the ordinary illusion of the stroboscope and moving-picture). Wertheimer attributed the phenomena to a 'physiologische Kurzschluss' between two regions of the cortex corresponding to the two points in visual space. Korte repeated Wertheimer's work and, carrying the problem still farther, subscribed to the same theory. Benussi, working with two successive pressure stimuli, found somewhat similar results and also favored Wertheimer's theory.

It would seem interesting, inasmuch as the visual and tactual are fields in which there is some plausibility for a correspondence between points of objective space and points in the cortex, to apply the same methods in another sense-department such as audition, where such a correspondence seems highly improbable. Accordingly the present study

[1] Wertheimer, M., 'Experimentelle Studien über das Sehen von Bewegung,' *Zeitschrift für Psychologie*, 1912, 61, pp. 161–265.

[2] Korte, A., 'Kinematoskopische Untersuchungen,' *Zeitschrift für Psychologie*, 1915, 72, pp. 193–296.

[3] Benussi, V., 'Kinematohaptische Erscheinungen,' *Archiv für die gesamte Psychologie*, 1913, 29, pp. 385–388. Benussi, V., 'Kinematohaptische Scheinbewegungen und Auffassungsumformung,' *Bericht VI Kongres für experimentelle Psychologie*, Göttingen, 1914, pp. 31–35.

attempted to repeat the work of Wertheimer and Korte in certain of its aspects in audition.

These investigators found, for instance, that an interval of about 60 sigma between stimuli gave, on the whole, the optimal impression of movement. With longer exposure of the lines, however, the optimal interval was relatively somewhat shorter. Moreover, by increasing the intensity of the second stimulus or by voluntarily directing the attention to it, apparent movement was frequently produced in the reverse direction. Further studies were made with different combinations of lines and with variations of distance and intensity, but only three problems were taken up in the present case:

1. The possibility of auditory illusions of movement.
2. The relation between exposure and interval.
3. The effect of difference in the intensity of the two stimuli.

Technical difficulties made it inadvisable to proceed farther with the present form of apparatus.

Apparatus and Method

The stimuli consisted of telephone receivers in series with a 250 vd. tuning fork on a 5-volt circuit. Normally the current passed through the fork directly. When, however, one side of the line was broken by relays actuated by a time-controlling mechanism the current was shunted through one of the receivers which gave a faint buzzing sound of the same pitch as the fork. One receiver was mounted on an arm moving synchronously with the time-mechanism. Two others were stationary. It was thus possible to produce an actually moving sound, a moving one with a break in the middle, or two separate successive sounds in different positions. For the first two cases it was merely necessary to close switches so that a single relay was operated once or twice, the current in each case passing through the moving receiver. For the two stationary receivers connections were made so that when one relay broke the current passed from the fork through the one receiver and when a second relay broke, the current

passed through the other receiver. Rheostats in series with all the receivers regulated the intensity of the stimuli.

A wooden disc, mounted upright, was rotated by an alternating-current motor reduced by belt gear and speed reducers. Various speeds were obtained by different combinations of gearing. Four brass contacts were clamped over the edge of this disc and held in place by set-screws on the rear side. Nearer the center were four concentric brass rings a few millimeters apart. These were connected through the disc by means of flexible wire to the rear of the four brass contacts. Brushes of spring brass pressed upon these rings, thus affording connections with the four contacts while the disc was rotating. A common pole of spring brass on one side of the main line brushed across the four contacts in succession. These latter passed to various connections operating the magnets of the relays. A telegraph key in series with the main brush enabled the whole line to be thrown on or off at any instant.

In some cases only two contacts were used, the width of the contacts giving the length of time the relay was broken, and hence the length of the sound, and the distance between the contacts giving the interval between the two sounds. For a wider range of adjustments a relay had the spring removed and a second set of magnets on the opposite side of the armature adjusted to just touch the armature when it was in its normal position. The residual magnetism of the cores held the armature there even though the relay was tipped slightly so that the armature tended to fall. The first contact on the disc (when the main brush passed across it) actuated the original magnets, pulling the armature down. It stayed there until the second contact actuated the other magnets pulling the armature back and holding it there by residual magnetism. The third and fourth contacts produced the same effect on a second relay arranged in the same manner. Thus by varying the distance between contacts and the speed of the disc, any desired exposure or interval could be obtained. The exposures and intervals were roughly calibrated by sending the alternating current with lamp resistance through

the relays and a signal magnet writing on a kymograph. This could be read accurately to 1/120th of a second. In some of the work the Hipp chronoscope was also used to measure the time.

The experiments were performed in the sound-proof room of the laboratory. The subject and the stimuli were in an inner room behind double doors. The stationary receivers were hung on the edge of a sound cage one meter in diameter. The subject sat either in the center of the cage or at a distance of two meters from the receivers. In some of the work a special rack with a black cambric screen between the receivers and the subject was used. The moving receiver was fastened to a wooden arm, the lower end of which was pivoted to a rod attached to the table edge. A horizontal rod pivoted to this arm passed through a small hole in the wall and was connected to a shaft operated by a crank attached to the rotating disc of the time-controlling mechanism. Thus the receiver oscillated synchronously with the exposures of the sounds through a distance of 70 cm. The receivers were all on the level of the ears of the subject who sat facing them on an adjustable chair. Preliminary experiments with the subject facing in various directions appeared to yield no significant facts except the more frequent confusion of direction of motion when the sounds were directly at one side, *i. e.*, at the end of the first or third quadrants, considering the eyes as facing zero. This would correspond to the usual confusion in the direction of sounds localized symmetrically with reference to the plane passing vertically through the two ears. The motor and tuning fork were in padded boxes so that the sound was minimized and what passed through into the inner room afforded little distraction but served rather as a warning signal.

At the beginning of the hour's work the receivers were equated in intensity according to the judgment of the subject. He was then simply told that when the light was extinguished he was to give his attention in the direction of the receivers and after the doors were again opened to describe what he had heard. The doors were then closed,

the fork started, the light extinguished and the time mechanism set in operation. Some time between the passing of the fourth and first contacts across the common brush the telegraph key was depressed and held down until the fourth contact had again passed, thus giving the stimuli in the desired arrangement. This arrangement was varied from day to day, sometimes continuously moving sounds intermixed with broken movement, sometimes moving sounds mixed with stationary ones.

Five subjects participated in the experiment, all graduate students with psychological training (one a woman). Only one was at all familiar with the problem and none were informed of the trend of results through the work, although all realized the difficulty of judging and were curious as to their efficiency. The experiments were performed in the Harvard Psychological Laboratory in the first half of the college year 1915–16.[1]

The present study is only of a preliminary nature. The stimuli were far from satisfactory. Although the intensity of the receivers could be adjusted by the rheostats there were invariably differences in timbre. These could be regulated to some extent by screwing the cap which confined the edges of the diaphragm. But undoubtedly the subjects almost always had timbre differences to assist them in distinguishing the discreteness of the two sounds, and hence the illusion took place less frequently and consistently. It would seem desirable to do more exhaustive work with tandem-driven tuning forks in boxes with small apertures, controlling the intensity by rotating the forks.

Results

The principal results for experiments with two sounds of equal intensity are summarized in Table I. The main interest lies, of course, in the trials in which two successive stationary sounds in different places yielded an impression of movement. The actually moving sounds and the broken moving sounds were introduced mainly as a check and to

[1] The writer expresses his obligations to the late Hugo Münsterberg.

avoid the subject's anticipating the character of the stimulus. These are not included in the table. The first few columns give the conditions investigated which yielded the optimal impression of movement for each subject; the next group those conditions in which the two sounds were always recognized as discrete and in different positions; and the last group those conditions in which this latter was nearly always the case but the illusion occasionally present. The first column in each group gives the time relations, *i. e.*, the time of the first sound, of the interval and of the second sound, in sigma. The second gives the distance apart of the receivers and the next the distance from the receivers to the subject's head, in centimeters. The fourth column in the first group indicates the per cent. of trials yielding the impression of movement, this percentage being based on from 10 to 20 trials. About this same number of trials forms the basis for the conditions in the other columns. There were few cases in which a single sound was heard. In the visual experiments the two lines were often seen simultaneously. In the auditory field this simultaneity would naturally resolve into a single sound midway between the sources. This occasionally happened, usually with intervals of 10 sigma or less, and the timbre differences in the receivers militated against such results.

The table shows that, under certain conditions of time and distance, two similar sounds in different positions with a definite time interval between, give the impression of a single moving sound.

It is to be noted first of all that one of the subjects does not appear in the table. This subject never reported movement on any of the trials with two separate sounds. Her auditory acuity was very good, according to her own statement, and it was quite manifest in the present case. Even with a single receiver moving and the sound broken in the middle of the movement she was seldom deceived, apparently catching the click as the diaphragm made its first contact with the magnet. On the last hour's experiment, however, as a result of suggestion she reported the illusion frequently. The experimenter intentionally expressed surprise at the

TABLE I

Subject	Optimal Movement				No Movement			Seldom Movement		
	Time	Distance			Time	Distance		Time	Distance	
A	190–33–190	18	200	80%	150–100–150	27	50	190–33–190	27	200
	76–10–76	18	200	75%	225–25–225	18	200	175–30–175	9	200
	76–10–76	27	200	100%	120–70–120	27	50			
	76–8–76	18	200	50%	120–48–120	20	200			
	68–54–68	18	200	83%	114–15–114	9	200			
					105–85–105	18	200			
					80–70–90	27	50			
					72–28–72	20	200			
					60–60–60	20	200			
Bu	90–10–90	18	200	66%	175–30–175	18	200	150–90–150	21	50
	67–6–67	18	200	50%	135–12–135	18	200	114–15–114	27	200
	47–38–47	18	200	66%	105–18–105	18	200	47–68–47	27	200
	47–38–47	27	200	50%	100–60–100	18	50			
	47–32–47	18	200	75%	79–55–79	18	50			
	47–32–47	27	200	75%						
	37–30–37	18	200	50%						
	37–30–37	27	200	66%						
C	225–25–225	27	200	66%	120–100–120	18	50			
	190–25–190	27	200	100%	90–10–90	27	200			
	180–48–180	10	200	100%	80–70–80	18	50			
	150–30–150	9	200	100%	70–80–70	18	50			
	150–30–150	18	200	100%	68–54–68	27	200			
	150–30–150	27	200	75%	66–100–66	18	200			
	150–30–150	36	200	66%	50–33–50	18	200			
	144–54–144	50	200	100%	33–25–33	18	200			
	144–54–144	60	200	100%						
	144–28–144	50	200	60%						
	114–15–114	27	200	100%						
	114–15–114	18	200	100%						
	108–28–108	10	200	75%						
	76–10–76	27	200	100%						
	72–28–72	10	200	66%						
	72–28–72	20	200	62%						
	67–7–67	27	200	85%						
	47–38–47	18	200	86%						
P	190–25–190	18	200	75%	175–30–175	18	200	150–90–150	21	50
	135–12–135	18	200	66%	120–48–120	10	200	144–54–144	10	200
	114–15–114	36	200	100%	100–70–100	18	50	144–54–144	20	200
	76–10–76	18	200	71%	79–55–79	18	50	144–54–144	30	200
	76–10–76	27	200	50%	76–16–76	18	200	144–54–144	40	200
	68–12–68	18	200	50%	58–68–58	9	200	144–36–144	10	200
					58–68–58	18	200	144–36–144	20	200
					58–68–58	27	200	144–36–144	40	200
								105–18–105	18	200
								90–8–90	18	200
								90–8–90	27	200
								72–28–72	10	200
								60–48–60	10	200
								67–6–67	18	200
								38–28–38	10	200

fact she never noted the actual motion of the sound, whereupon she did note it repeatedly.[1]

There are further individual differences evident. *C* manifests the illusion to a far greater extent than any of the others, reporting it not only under more settings but also in a larger per cent. of trials on a given setting. In some instances the illusion was successful with the receivers 50 or 60 cm. apart. He stated that it was 'usually easy to tell which way they go and to tell one from two.'

P's results, on the other hand, fall mostly in the group in which the illusions occurred but seldom on a given setting. He often noted however a peculiar 'feeling of movement' in addition to the perception of the two discrete sounds. To quote his introspection: "Sometimes get two sounds but a distinct feeling of movement. I rationalize it with the stick moving and so get a feeling of movement." Or again: "Two sounds but an impression of movement besides. Get idea it is the same sound travelling. Have often some visual scheme, *e. g.*, like sticks on a fence. The feeling itself unanalyzable, like the feel of a band going down the street; sort of an interpretation of the thing." He noted at another time that, "If the sounds move at about the proper rate to coincide with what I think is moving I get the impression of movement."

A reported the illusion in only a few conditions and these were mainly near the outset of the experiment. Toward the end he became sceptical. He seemed to judge much by the after-image. The following introspections are typical: "Judgments afterward, like seeing a mass of things on a screen and analyzing it;" "Distinct image afterward and look at the sound picture." Toward the end of the experiments he admitted that he was sceptical and thought 'the apparatus fitted for only two sounds.'

Bu showed the illusion in a number of settings. He noted

[1] This effect of suggestion in producing the illusion indicates the advisability (with some subjects at least) of proceeding as in the present case without explaining the nature of the experiment, rather than following the methods used in the visual studies where the subject knew all about it and was required to state whether he perceived the illusion or not.

that it was easier to tell the direction in which the sound was moving than to tell one from two sounds. He found that much too depended on the attention. "If you wait too long it catches you on the wrong wave."

It is to be noted further that the illusion almost never occurred with the subject in the sound-cage, *i. e.*, 50 cm. from the receivers. Presumably the intensity of the stimuli was too great or their timbre differences too pronounced at that distance, even though the current was reduced as far as it was possible to do and still keep the fork going.

Wertheimer and Korte found that in general an interval of some 60 sigma between the two stimuli a few centimeters apart gave the optimal impression of visual movement. The above table would indicate a somewhat shorter interval as yielding optimal results in the auditory field,—ranging from approximately 10 to 50 sigma with the average 25 or 30. This may correspond to the usual finding that auditory reactions are quicker than visual.

The above investigators also found that the longer the exposure the relatively shorter is the optimal interval. A glance at the first column of the table shows that such was the case in the present study. The rows in the column are arranged for each subject in order of magnitude of the *exposure* with the longest at the top. It will be seen by following the *intervals* down the column, that in many cases they grow actually longer as the exposure decreases and in almost all cases relatively longer. There were a number of instances in which trials were made on a given subject with the exposure and interval in the same ratio while the absolute values were changed. Such series are grouped separately in Table II. The designations of the separate columns are the same as those of the first two divisions of Table I., but figures grouped together in a given row are those in which the ratio of interval to exposure time is constant. For example the first row indicates that with exposures of 76 sigma and an interval of 10, apparent movement was often perceived, while with exposures of 114 and interval of 15, which was in the same ratio as the first conditions, movement was never apparent. It is evident

that with three of the four subjects, given exposure and interval in the same ratio, the longer absolute values yield no movement while the shorter do. That is, the longer the exposure, the relatively shorter is the optimal interval.

TABLE II

Subject	Optimal Movement			No Movement		
	Time	Distance		Time	Distance	
A	76–10–76	18	200	114–15–114	9	200
	76–10–76	27	200			
B	67–7–67	18	200	135–12–135	18	200
	47–32–47	18	200	79–55–79	18	50
	47–32–47	27	200			
C	225–25–225	27	200	90–10–90	27	200
	47–38–47	18	200	68–54–68	27	200
				33–25–33	18	200
P	68–12–68	18	200	175–30–175	18	200

The other factor of interest in the present study was the effect of varied intensity. It was found in the visual experiments that, given the optimal conditions for apparent movement, increasing the intensity of the second stationary stimulus produced apparent movement in the reverse direction. This factor was studied in the present case for a few of the optimal time relations by adjusting the rheostats in series with the receivers. The sounds were equated in intensity at the beginning of the hour's work according to the judgment of the subject, and during the hour the rheostat in series with the second receiver was varied. The intensity of the sound was not measured, but four different settings of the rheostat were intermixed irregularly with the normal setting. Table III. gives the results found in this manner with two stationary receivers and the intensity of the second sound equal to or greater than that of the first. The first columns give the time of exposures and intervals and the distance of the receivers from one another and from the subject as in Table I. Then follow the per cent. of trials in which normal and reverse movement was produced in trials with the intensities equal and in trials with the second sound louder than the first.

Normal movement, of course, signifies apparent movement in the direction in which the temporal succession of the sounds actually occurred. The results in a given row in the table were always obtained on a single day.

TABLE III

				Equal Intensity		Second Sound Louder	
	Time	Distance		Normal Movement	Reverse Movement	Normal Movement	Reverse Movement
A	190–33–190	18	200	60%	20%	0%	50%
	190–33–190	27	200	40%	0%	40%	20%
	76–10–76	18	200	75%	0%	27%	18%
	76–10–76	27	200	100%	0%	0%	0%
	76–8–76	18	200	50%	0%	60%	20%
B	67–6–67	18	200	25%	25%	0%	66%
	47–38–47	18	200	50%	0%	0%	0%
	47–38–47	27	200	0%	66%	0%	100%
	47–32–47	18	200	50%	25%	0%	25%
C	190–25–190	27	200	50%	50%	33%	66%
	114–15–114	27	200	66%	33%	43%	57%
	108–28–108	10	200	75%	12%	0%	60%
P	135–12–135	18	200	66%	0%	66%	0%
	90–8–90	18	200	40%	0%	0%	0%
	67–6–67	18	200	33%	0%	0%	0%
Average				52.0%	15.4%	17.9%	32.1%

It is quite evident from the averages that the reversal effect is often produced by an increase in the intensity of the second stimulus. Whereas with stimuli of equal intensity the illusion of movement in the same direction as the actual temporal succession occurs in 52 per cent. of the trials and in the reverse direction in only 15 per cent., with the second stimulus louder the illusion in the normal direction occurs in only 17 per cent. of the trials and in the reverse direction in 32 per cent.

SUMMARY

1. The presentation of two faint similar auditory stimuli in quick succession a few centimeters apart yields, under certain conditions, an impression of a sound moving in the direction of the actual temporal succession of the stimuli. Individuals vary in their susceptibility to the illusion but four of the five subjects used manifested it at various times.

For the fifth subject imperfect technique combined with marked auditory acuity perhaps accounts for the results. A time interval between the sounds of 25 to 30 sigma yields on the whole the optimal impression of movement.

2. There appears a rather definite relation between the length of the period of exposure and of the interval between the stimuli. The longer the exposure, the relatively shorter must be the time interval to yield the optimal impression of movement.

3. If the intensity of the second stimulus is greater than that of the first the apparent movement is often in the reverse direction.

Conclusions

As far as the experiment was carried, the results were strikingly similar to those of Wertheimer and Korte. This fact necessitates a reconsideration of Wertheimer's theory. The fundamental assumption of this theory is that stimuli at various points in visual space are correlated with disturbances in corresponding regions of the visual cortex and that there is a 'physiologische Kurzschluss' between these cortical regions. Corresponding to this Kurzschluss there is the perception of (illusory) movement between the original external points. Increasing the intensity of the second stimulus can sometimes reverse the direction of this 'Kurzschluss.' The finding by Benussi of similar results in tactual space does no violation to the theory, for a similar assumption may be made of a correlation of different points on the skin with different points in the cortex and of a physiological 'Kurzschluss' between such cortical regions. But with audition it is a different matter. The auditory end organs are not stimulable at different points as are the retina and the epidermis. There is no evidence for the correlation of separate points in auditory space with separate regions of the sensory cortex. Wertheimer's theory cannot explain the results of the auditory experiments as it does those of the visual. Yet the same subjective phenomena are manifested in both cases. The implication is that there must be some additional factor operative in both audition and vision.

The writer is inclined to explain the phenomena on the basis of the 'action theory.' A sound at the level of the ears produces, by its binaural intensity difference, a motor impulse to turn the head or eyes in its direction. If a second sound in the same plane and at the same height supervenes shortly, there is a second motor impulse, presumably in the same centers, before the first is completely exhausted. The position of the sounds may thus be represented cortically by impulses of different intensity in the motor regions leading to the same muscles of the eyes or neck. If the second sound supervenes rapidly enough there is a continuity of the motor impulse. The direction in which the second impulse would lead, if executed, relative to the first, gives the cue as to the direction of motion. With the increase of intensity of the second stimulus it is conceivable that the second motor impulse is temporally facilitated sufficiently to produce the effect which would have obtained had it actually preceded. It is well known that reaction time decreases with the increase of the intensity of the stimulus.[1]

Some such factor as the above may well be involved in the similar visual and tactual phenomena. It seems probable that a visual or tactual stimulus produces an impulse to make some muscular adjustment in order to more clearly perceive the source of the stimulus. The biological importance of such a tendency is obvious. A second stimulus may produce an additional impulse before the first is exhausted and the continuity of the two gives the illusion of movement. At least it seems that a different theory from Wertheimer's is necessary to account for the auditory illusions. Perhaps this same theory may be involved in the visual and tactual inasmuch as they manifest the same characteristics. The writer hazards the belief that it is a question of the continuity of the motor impulses.

[1] Cf. Pieron, H., 'Recherches sur les lois de variation de temps de latence sensorielle en fonction des intensites excitatrices,' *L'Annee Psychologique*, 20, 1914, 17–96.

A COMPARISON OF DEAF AND HEARING CHILDREN IN VISUAL MEMORY FOR DIGITS

BY RUDOLF PINTNER AND DONALD G. PATERSON

Ohio State University *University of Kansas*

In the course of other individual tests with deaf children an attempt was made to measure the deaf child's immediate memory. One prerequisite for such a plan involves the presenting of relatively non-significant material in serial order to the subject who tries to reproduce the material in correct order and exactly as presented. This requirement was met by using digits arranged and presented serially, care being taken to avoid any commonly associated groupings such as historic dates or ordinary sequence, *i. e.*, 4, 5. Digits are relatively non-significant and as given in this series of experiments afford a fairly reliable index of the subjects' rote memory.

Four hundred and eighty-one deaf children were tested individually. They were all pupils attending the Ohio State School for the Deaf[1] during the school year 1914–15. The youngest pupil was seven years old, while the oldest pupil tested was twenty-six years of age. The smallest number tested in any one age was 15 (at age 7). The largest number was 51 (at age 16). All pupils of 19 years or more are grouped together and arbitrarily called adults.

The method used closely approximates that developed by Whitley.[2] A box whose inside measurements were $\frac{1}{2}$ by $1\frac{1}{4}$ by $15\frac{1}{4}$ inches was made with an aperture in the top measuring $\frac{3}{4}$ by $\frac{3}{4}$ inches. One end of the box was left open. Strips of

[1] The writers wish to acknowledge the kindness and coöperation shown them by the superintendent, Mr. J. W. Jones, the principal, Dr. Robert Patterson and the several teachers.

[2] Whitley, Mary T., 'An Empirical Study of Certain Tests for Individual Differences,' *Archives of Psychology*, No. 19, 1911, New York, The Science Press, p. 50.

cardboard were inserted in the open end of the box. The top card was then withdrawn slowly, exposing one digit at a time for about one second. There were two exposures of the same length of digits. Series of digits began with two digits and ended with seven. The score recorded was a plus or minus for each series of digits. Wrong order was counted minus. The digits were printed in blue type and measured ¼ inch in height. They were large enough to be seen clearly by every subject. After each series had been exposed, the subject immediately recorded in pencil on paper what he could remember. The series were always presented in the same order, beginning with the shortest and ending with the longest.

The memory span of each individual was determined by taking the highest series of digits reproduced correctly, irrespective of previous failures with fewer digits. This method approximates that used by Smedley.[1] By disregarding previous failures with fewer digits we are intentionally giving the advantage to the deaf child. His memory span as here recorded is probably a little higher than it would have been, had we used exactly the same method used by Smedley in determining the memory span of the hearing child.

The results are presented below in tabular and graphic form. A comparison is made between the oral pupil and the manual pupil, between the hearing child and the deaf child, between the deaf boy and the deaf girl, and between the congenitally and the adventitiously deaf.

Table I. and Graph I. show the comparison of the oral pupils with the manual pupils. The horizontal column at the top of Table I. gives the ages, the second column the numbers tested at each age, the third column the average memory span at each age, the next the span of 75 per cent. of the pupils, the next the span of the median pupil and the last horizontal column gives the span attained by 25 per cent. of the pupils. For example, there are 27 twelve-year-old orally taught deaf children. Their average memory span is 3.2;

[1] Smedley, F. W., Child Study Report No. 3 of the Department of Child Study and Pedagogic Investigation, Chicago Public Schools, 1900–1901, p. 53.

TABLE I

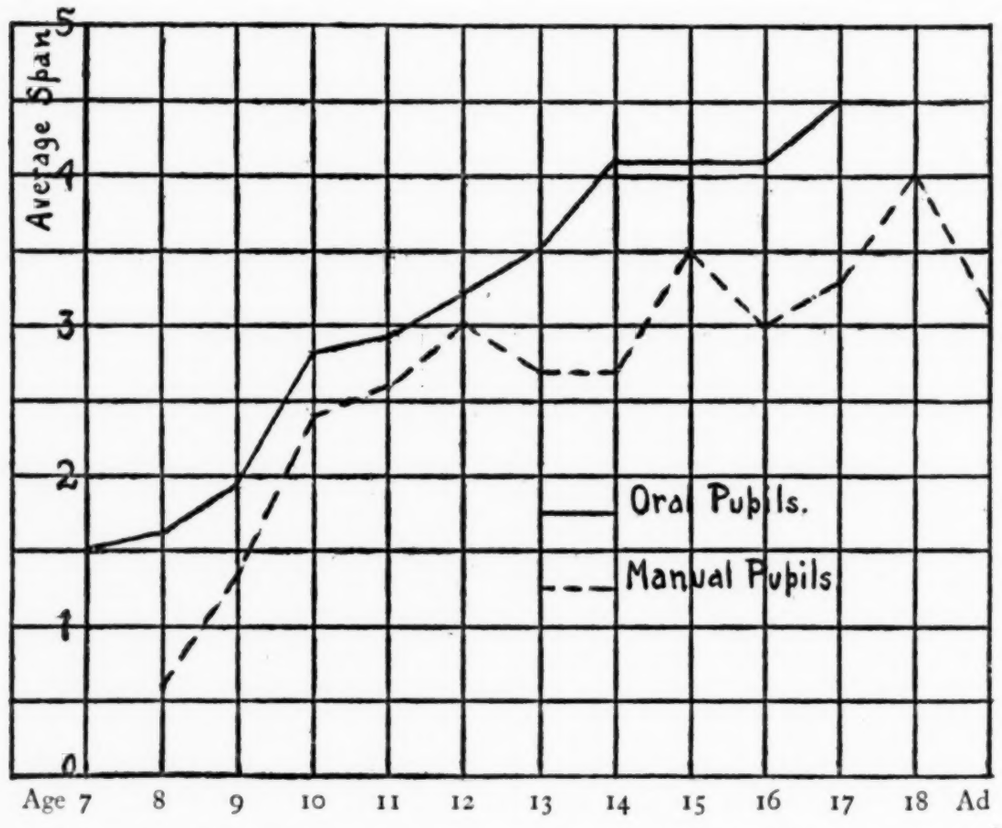
COMPARISON OF THE ORALLY TAUGHT PUPILS WITH THE MANUALLY TAUGHT PUPILS IN VISUAL MEMORY

Oral Pupils

Age.....	7	8	9	10	11	12	13	14	15	16	17	18	Adults
Number.....	15	22	20	38	33	27	27	13	20	28	17	13	26
Average.....	1.5	1.6	1.9	2.8	2.9	3.2	3.5	4.2	4.2	4.2	4.5	4.5	4.5
75 percentile...	0	0	0	2	2	2	3	3	4	3	4	4	4
Median.....	2	2	2	3	3	3	3	4	4	4	4	5	4
25 percentile...	2	3	3	3	3	4	4	5	5	5	5	5	5

Manual Pupils

Number.....		3	11	8	17	16	15	14	13	23	30	13	19
Average.....		0.6	1.3	2.4	2.6	3.0	2.7	2.7	3.5	3.0	3.3	4.0	3.1
75 percentile...		0	0	2	2	2	2	2	3	3	2	3	3
Median.....		0	0	3	3	3	3	3	3	3	3	4	3
25 percentile...		2	3	3	3	4	3	4	4	3	4	5	3



GRAPH I. Comparison of the Average Memory Span for Digits for Oral and Manual Pupils at Each Age.

75 per cent. of them have a span of at least two digits, the middle or median child has a span of 3 digits while 25 per cent. of them have a span of 4 digits or more. By referring to the lower half of the table we find that there are 16 twelve-year-old manually taught deaf children. Their average span is 3.0; 75 per cent. of them have a span of at least 2 digits, the median pupil has a span of 3 digits and 25 per cent. of them have a span of 4 digits or better. There is little difference between the two groups at this age. A comparison of the two groups, however, shows that this is not the case at other ages. Oral pupils, age 8 and 9, are superior to manual pupils of the same ages as shown by the medians. At ages 10, 11, 12, and 13 the medians show the two groups to be of equal ability. From age 14 on the medians show the oral pupils to be superior.

The averages for the two groups are shown in Graph I. The curves show clearly that at every age the oral pupils are superior to the manual pupils. These results are to be expected. Oral enthusiasts might be inclined to say that the oral method, which uses the teaching of speech and lip-reading as the sole means of instruction, is the causal factor in the superior memory ability of the oral pupils. This position is untenable because of a selective factor which operates to the advantage of the oral pupils. All pupils on entering the institution are instructed by means of the oral method. Those who fail to progress under this method are then relegated to the manual classes in which instruction is carried on by means of the manual alphabet and sign language. This failure to profit by the oral method is often due to inferior ability in other respects. In this test the inferiority is shown by a shorter memory span, on the average.

Table II. gives the data for all the deaf children and also the hearing children tested by Smedley and the deaf children tested by MacMillan and Bruner.[1] Graph II shows the relative abilities of the deaf children tested by us and the hearing children tested by Smedley.

[1] MacMillan, D. P. and Bruner, F. G., A Special Report of the Department of Child Study and Pedagogic Investigation on Children Attending the Public Day-Schools for the Deaf in Chicago. Chicago, 1908, pp. 70–71.

In the first part of Table II. we have given the actual distribution of the deaf children at each age. At age 7 for example 4 children had a memory span of 0, *i. e.*, less than 2; 10 had a span of 2 digits, and one a span of 3 digits. The total number tested at age 7 was 15, their average span 1.5, etc. The averages for the deaf children show a tendency to increase in memory ability from age to age. Those classed as adults have a lower average span than the 18-year-olds. This may mean that the 18-year-old pupils are on the average much better than would be expected in light of the scores of the ages below 18, or that the adult pupils are slightly poorer than they should be. Either factor or both may account for the results.

It will be seen that only 5 of the deaf pupils have a memory span of 7 digits. These are all oral pupils. Of the 16 deaf pupils who attained a score of 6 digits only 3 are manual

TABLE II

MEMORY SPAN OF DEAF AND HEARING CHILDREN

All Deaf Children

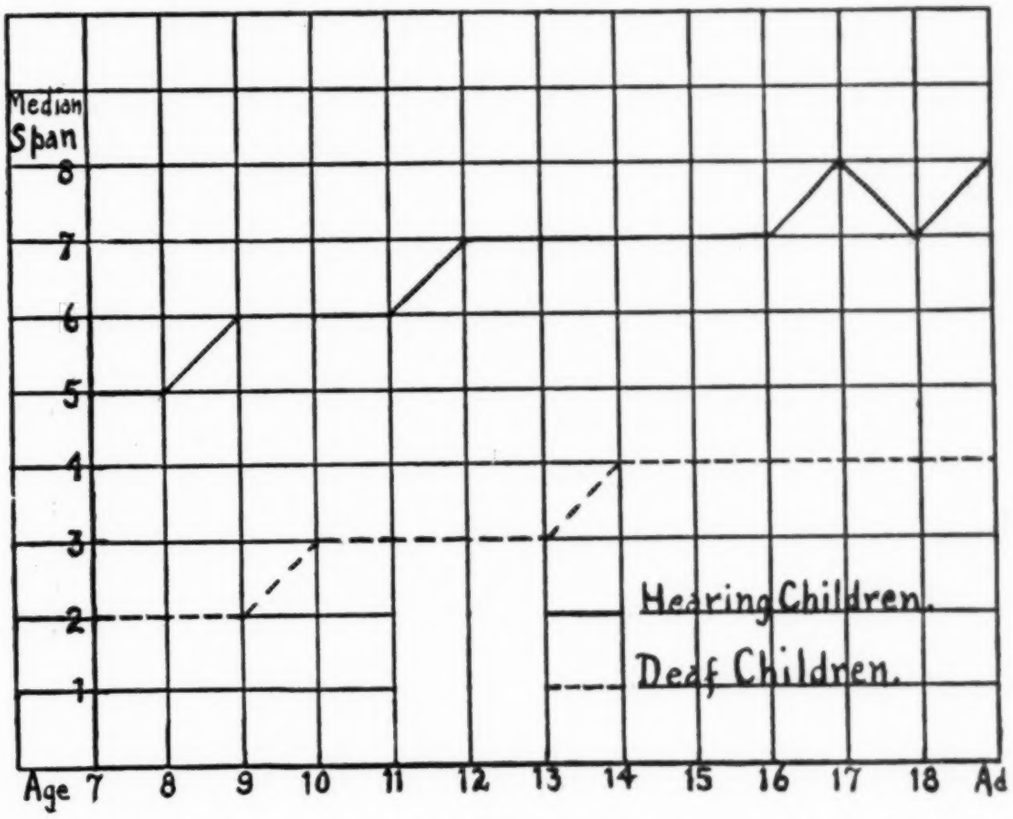
Age.....	7	8	9	10	11	12	13	14	15	16	17	18	Adults
0	4	10	12	2	1	1	1	2					
2	10	8	9	16	14	10	8	4	2	7	7		2
3	1	7	7	20	30	18	18	7	9	18	11	6	19
4			2	5	1	11	10	9	14	13	20	10	12
5			1	3	4	2	3	3	6	10	6	7	7
6						1	2	1	1	3	2	3	3
7								1	1		1		2
Number.....	15	25	31	46	50	43	42	27	33	51	47	26	45
Average.....	1.5	1.5	1.7	2.8	2.8	3.1	3.2	3.4	3.9	3.7	3.7	4.3	3.9
75 percentile...	0	0	0	2	2	2	3	3	3	3	3	4	3
Median.....	2	2	2	3	3	3	3	4	4	4	4	4	4
25 percentile...	2	3	3	3	3	4	4	4	5	5	4	5	5

Hearing Children (Smedley)

Age.....	7	8	9	10	11	12	13	14	15	16	17	18	19
Span.....	5	5	6	6	6	7	7	7	7	7	8	7	8

Chicago Deaf Children (MacMillan & Bruner)

Age.....	7	8	9	10	11	12	13	14	15	16	17	18	19
Number.....	10	13	13	17	12	7	12	12	17	6	4	2	2
Average span ..	3.3	3.3	3.7	4.1	4.4	4.7	4.8	5.2	4.9	5.7	5.5	5.0	5.0



GRAPH II. Comparison of the Median Memory Span of Deaf and Hearing Children.

pupils. Of the 52 pupils who have a memory span of 5 digits only 7 are manual pupils. The more efficient among the deaf pupils are predominantly the oral pupils.

In comparing the averages of the deaf children tested by us with those tested by MacMillan and Bruner we note that the Chicago Day-School deaf children are superior at every age. Several factors have combined to bring about this result. The Chicago deaf children reproduced the digits 'either orally or in writing.'[1] This is a variation in method which might greatly favor the Chicago children, since difficulty in writing possessed by any one child could be overcome by oral reproduction. It may be that there is a difference between results when reproduction is tested orally or written. It would seem to the writers that one method ought to be adhered to throughout. Further there was a

[1] MacMillan and Bruner, *ibid.*, p. 70.

high degree of selection among Chicago children tending to make them superior while the selection among the children tested by us was in the reverse direction. MacMillan and Bruner in their report (page 4) state that 10 per cent. of the deaf children in the day schools of Chicago were pronounced subnormal and excluded from the schools and sent to institutions in 1902 and further that since 1902 (page 73 of the report) "no feeble-minded children were permitted to enroll in the classes for the deaf." Such care in the selection of the deaf children in the day schools has without doubt appreciably raised the average ability of the children tested by MacMillan and Bruner. In Ohio there were five public day schools in as many cities during 1914–15. There was no doubt a tendency for the brighter deaf children to remain at home and attend these day schools while the duller ones from these same cities went to the state institution where they were maintained at public expense. Thus the selection works to the disadvantage of the state school. These are the factors which account for the evident superiority of the Chicago deaf children on this test. The comparison of the two groups of deaf children indicates the powerful influence that incidental factors such as variation in method and differences in selection of children may exert and hence warns us to analyze critically all the factors involved in comparative psychological studies.

Graph II. presents the curves representing the median memory spans of the deaf children tested by us and the hearing children tested by Smedley. It is rather startling to find that the average deaf child at any age never equals the average ability of seven-year-old hearing children. This difference is not shown on other mental tests. In learning ability the average retardation of these same deaf children on the Digit-Symbol test[1] was only three years. It is to be noted that both tests require the use of digits in their performance hence the marked inferiority of the deaf children in

[1] Pintner, R., and Paterson, D. G., 'A Class Test with Deaf Children,' *The Journal of Educational Psychology*, Vol. VI., No. 10, Dec., 1915, pp. 591–600. Also 'Learning Tests with Deaf Children,' *The Psychological Review Monograph Supplements*, Vol. XX., No. 4, Whole No. 88.

visual memory cannot be laid at the door of the materials used in this test.

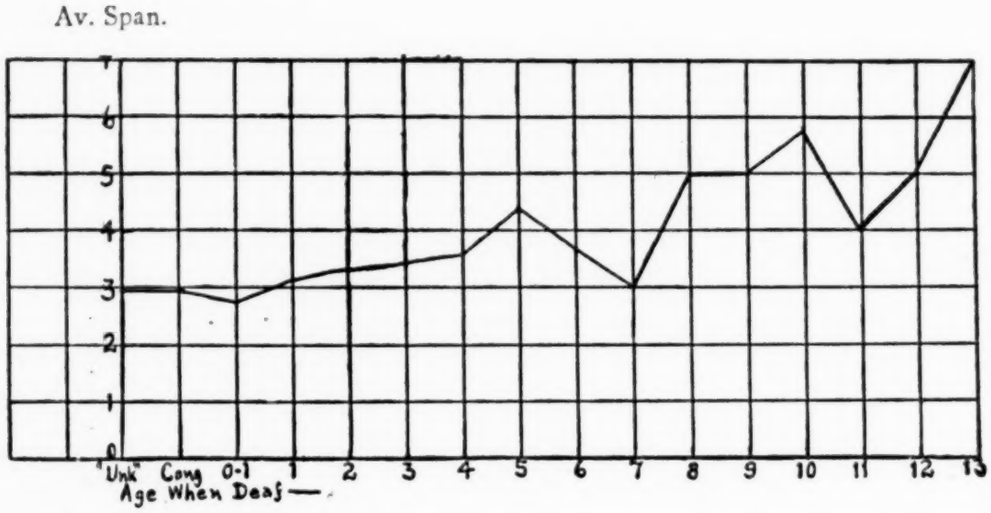
The cause of this disparity between the two groups must be sought in another direction. It is revealed by an analysis of the mental processes involved in this test. The hearing individual (in most cases probably) uses auditory images (consisting of the sound of the digits) plus inner tactual sensations aroused by the innervation of the muscles controlling the vocal chords, tongue and larynx. There may also be involved kinæsthetic imagery related to the hand movements necessary to write the digits. For the most part the auditory factor is eliminated for the deaf subject. This leaves the deaf child dependent for his memorization and recall mainly upon the visual percept, which becomes a visual image after the withdrawal of the stimulus. Many of the deaf children used their hands during the perceptual process, spelling out the digits as they were exposed. Many of them also used inner speech as indicated by lip movements. Hence memorization visually was in many cases aided by secondary sensory processes. Of course, a deficient nervous system caused either by poor heredity or the ravaging diseases which often cause deafness, probably accounts for much of the backwardness of the deaf in this test. But the results obtained in the Digit-Symbol test lead us to emphasize what is more probable, namely, the importance of audition in aiding the visual memory.

That the auditory factor is important is clearly brought out by Tables III. and IV. and Graphs III. and IV. Table

TABLE III

AVERAGE MEMORY SPAN OF DEAF CHILDREN. DISTRIBUTION ACCORDING TO AGE AT WHICH DEAFNESS OCCURRED

Age When Became Deaf...	Unknown	Cong.	0–1	1	2	3	4	5	6	7	8	9	10	11	12	13
Number..	52	206	32	62	55	27	14	13	6	2	1	3	4	1	2	2
Total score...	154	608	89	193	185	92	50	57	22	6	5	15	23	4	10	14
Average score...	2.96	2.95	2.78	3.11	3.36	3.41	3.57	4.38	3.66	3.0	5.0	5.0	5.75	4.0	5.0	7.0



GRAPH III. Average Memory Span of Deaf Children according to Age at which Deafness Occurred.

III. shows the grouping of the deaf children according to the age when they became deaf. The column headed 'unknown' includes all the cases whose records state that the time of the occurrence of deafness is unknown. That marked 'Cong.' includes those born deaf, that headed 0–1 those becoming deaf before they were a year old, etc. This table shows that the average efficiency tends to increase with the number of years of auditory experience prior to the deafness. The two deaf children who did not become deaf until they were 13 years of age have normal visual memory ability. There is a close correspondence in the first three columns. The 'unknown' cases do just about as well as the 'congenital' cases. This leads one to suspect that probably most of those cases recorded as 'unknown' were in reality born deaf. We seem to have experimental evidence which corroborates the statement of the superintendent of the Indiana Deaf School to the effect that probably two thirds of the cases recorded as 'unknown' are congenital deaf.[1] The conclusion to be drawn from a study of Table III. and Graph III. seems to be that in general the greater the previous auditory experience of the group the greater is the efficiency in immediate memory for digits.

[1] Johnson, R. O., 'Some Statistics Concerning Deafness,' Bulletin issued by the Indiana State School for the Deaf, p. 14.

Table IV. and Graph IV. show a comparison of the congenital deaf pupils with the adventitious pupils in visual memory for digits and in learning ability as tested by the Symbol-Digit test.[1] We find that the adventitious (cases in which the deafness is acquired or more precisely has developed after birth) are superior at every age, with the exception of age 9, to the congenitally deaf in memory for digits. This is not so when the learning test is considered. The conclusion to be drawn seems to be that in immediate memory previous auditory experience is of considerable importance as contrasted with another type of test that involves the same materials, *i. e.*, digits. It seems then that the startling backwardness of the deaf child in visual memory is in large part due to his lack of auditory experience.

TABLE IV

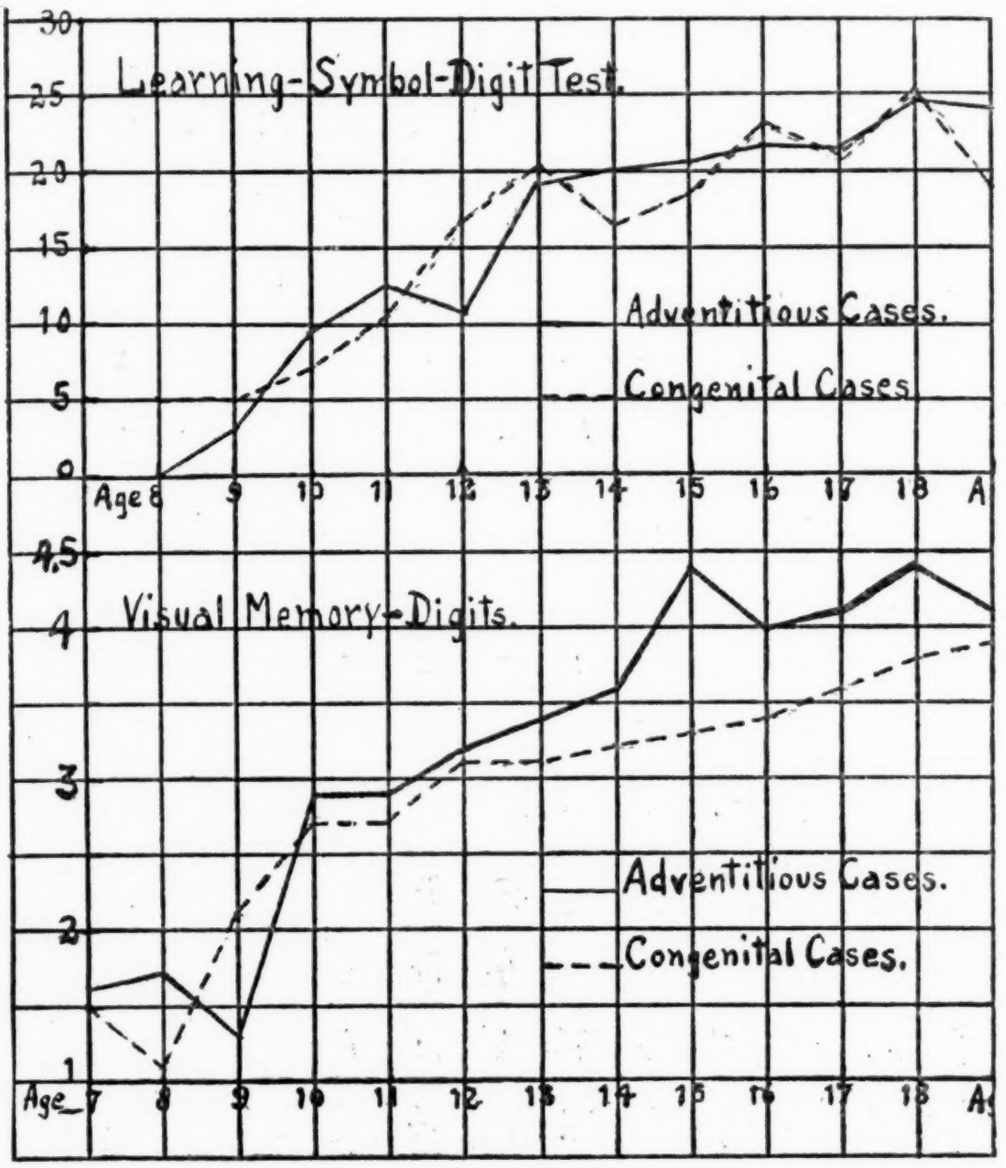
COMPARISON OF THE CONGENITALLY AND ADVENTITIOUSLY DEAF IN VISUAL MEMORY FOR DIGITS AND LEARNING ABILITY AS TESTED BY THE SYMBOL-DIGIT TEST

Age	Visual Memory—Digits				Learning—Symbol-Digit Test			
	Congenital		Adventitious		Congenital		Adventitious	
	No.	Average	No.	Average	No.	Median	No.	Median
7	10	1.5	5	1.6				
8	13	1.1	12	1.7	5	5.0	4	0
9	15	2.1	12	1.3	8	5.0	8	3.3
10	25	2.7	20	2.9	22	7.4	15	9.8
11	22	2.7	24	2.9	22	10.6	21	12.2
12	21	3.1	19	3.2	16	16.9	22	10.7
13	15	3.1	19	3.4	11	20.4	22	19.3
14	11	3.2	13	3.6	16	16.7	17	20.0
15	14	3.3	13	4.4	15	18.8	24	20.5
16	23	3.4	22	4.0	24	23.4	19	21.8
17	15	3.6	25	4.1	10	20.9	28	21.0
18	9	3.8	17	4.4	11	25.4	21	24.6
Adults	14	3.9	28	4.1	14	19.0	32	24.0

Without attempting to enter into a lengthy discussion these results tend to discredit the widely accepted and prevalent theory concerning the vicarious functioning of localized portions of the nervous system. Here we have shown that the so-called visual center seems to have failed to take upon itself the functions of the auditory center and

[1] Results here given are taken from the Monograph previously referred to.

that compensation seems to be conspicuous because of its absence.


Learning-Symbol-Digit Test.
Adventitious Cases.
Congenital Cases
Age 8 9 10 11 12 13 14 15 16 17 18 A
Visual Memory-Digits.
Adventitious Cases.
Congenital Cases.
Age 7 8 9 10 11 12 13 14 15 16 17 18 A

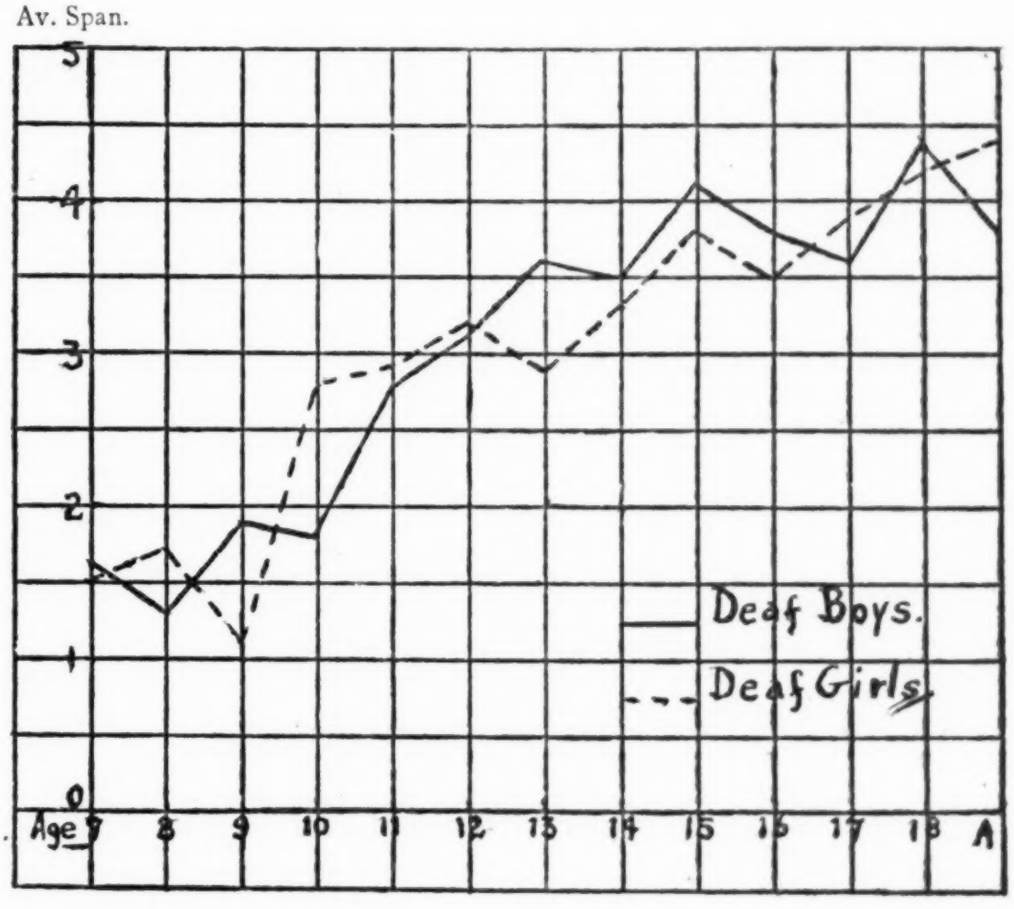
GRAPH IV. Comparison of Deaf in Visual Memory and Learning.

Are there any pronounced sex differences among the deaf pupils in visual memory? Table V. and Graph V. present the averaged results for the two sexes. Inspection of the table and graph shows that there is no constant sex difference. The curves of the two sexes cross each other repeatedly and one must conclude that a sex difference is lacking. Among

TABLE V

COMPARISON OF DEAF BOYS AND DEAF GIRLS IN VISUAL MEMORY FOR DIGITS

Age	Deaf Boys		Deaf Girls	
	No.	Average	No.	Average
7	7	1.6	8	1.5
8	14	1.3	11	1.7
9	23	1.9	8	1.1
10	23	1.8	23	2.8
11	33	2.8	18	2.9
12	28	3.1	14	3.2
13	18	3.6	24	2.9
14	13	3.5	14	3.3
15	15	4.1	18	3.8
16	31	3.8	20	3.5
17	22	3.6	25	3.9
18	11	4.4	15	4.2
Adults	21	3.8	17	4.4



GRAPH V. Average Memory Span of Deaf Boys and Deaf Girls.

hearing children there seems to be a superiority of the girls,[1] but here as in the case of the learning tests there is no sex difference.

Summary

In summarizing the results of this test the following points are of importance.

1. Oral pupils are superior to manual pupils on the average.
2. Deaf children as a group have an abnormally poor memory span due to the lack of auditory experience.
3. Adventitiously deaf children are superior to congenitally deaf children on the average.
4. Auditory experience plays an important part in the efficiency of both hearing and deaf individuals in visual memory for digits.
5. Sex differences do not exist among the deaf in this test.

[1] Whipple, G. M., 'Manual of Mental and Physical Tests,' Part II., pp. 179–184, Baltimore, Warwick and York, 1915.

A NEW COMPLICATION APPARATUS

BY KNIGHT DUNLAP

THIS piece of apparatus was designed for use by a new method described below, requiring a large, clear dial. It was also deemed advisable to construct an instrument which would give ease and accuracy in setting a discrete stimulus in its proper place and such that the discrete stimulus would not vary in intensity with the rate of rotation. I believe that these problems have been satisfactorily solved in the present apparatus.

The apparatus consists essentially of a cast iron base, *A*, upon which are supported two pillars, B_1, B_2, 26 cm. high and 26 cm. apart. On the front of one of these pillars, B_1, is supported a dial, *C*, 36 cm. in diameter; on top of the pillars are brass bearings through which and through the center of the dial plate runs the main shaft, *E*. This shaft carries on the front of the dial an index hand, *F*—several hands of different length and shape are used. Just behind this support the shaft carries an arm, *G*, which can be clamped in any angular position with regard to the dial hand by means of a set screw and to which is attached a vernier scale, *H*, reading to degrees. By the use of the vernier the settings are made very easy, since the graduations on the circular scale are in ten degree units. Close to the other pillar, B_2, the shaft carries a large gear wheel, *I*, and a swinging arm, *J*, carrying a double gear, *K–L*, the smaller one of which is in mesh with the gear, *I*, on the shaft. This swinging arm can be locked in any position by means of a set screw in the pillar and passing through the slot in an L-shaped branch of the arm. The large gear on the arm is in mesh with the small gear on the shaft of the motor, *M*, fastened to the base of the instrument. By means of the swinging arm adjustment it is possible to use various sizes of gear on the motor shaft.

The adjustable arm attached to the vernier scale carries on its outer end a small horseshoe magnet, *N*. A vertical contact-lever, *O*, is carried on a support attached to the front pillar and in such position that the poles of the rotating horseshoe magnet, *N*, pass above and close to an iron crossbar on the top of the lever. A second horseshoe magnet, *D*, fixed on the support of the contact-lever keeps the contact closed until the traveling magnet, *N*, passes by and momentarily opens it. This contact device obviates the greater part of the noise which results from a mechanical contact breaker of the ordinary type and gives perfectly satisfactory contact. Since the vernier, *H*, and the index hand, *F*, are both adjustable on the shaft, the vernier may be set so that it reads zero when the index hand is actually at zero on the dial. Once set in this position, all further readings on the vernier will correspond to the readings on the index dial.

In order to secure a clean, single sound of intensity not varying with the rate of the interruption, an automatic relay[1] is employed in connection with a telephone receiver. The telephone receiver is mounted at the end of a wooden resonance chamber, somewhat like a megaphone, which greatly increases the sound. The primary circuit of the induction coil is interrupted by the contact breaking device on the complication apparatus. A secondary circuit which passes through the telephone receiver is interrupted on each side of the coil by two levers magnetically attracted by the core of the coil. When the current is flowing through the coil, the secondary circuit, *i. e.*, through the telephone receiver, is closed. At the moment of interrupting the primary circuit, therefore, the induced circuit flows through the telephone, producing a loud snap. Immediately thereafter, the core ceases to attract the levers and the circuit through the telephone receiver is broken on both sides of the core; consequently, when the primary circuit is reëstablished no secondary current is induced through the telephone circuit. In this way the break-current alone is used. By changing the

[1] This automatic relay was exhibited at the 1915 meeting of the American Psychological Association.

COMPLICATION MACHINE

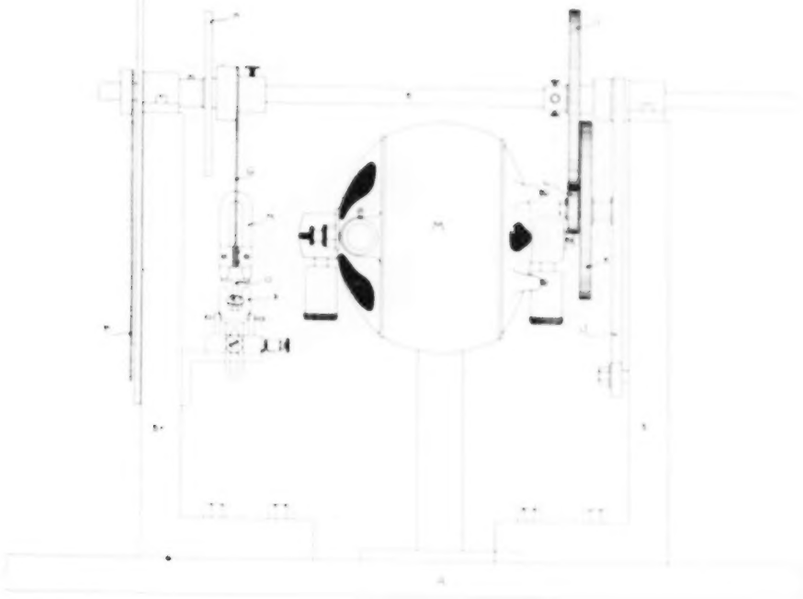


Fig. 1.

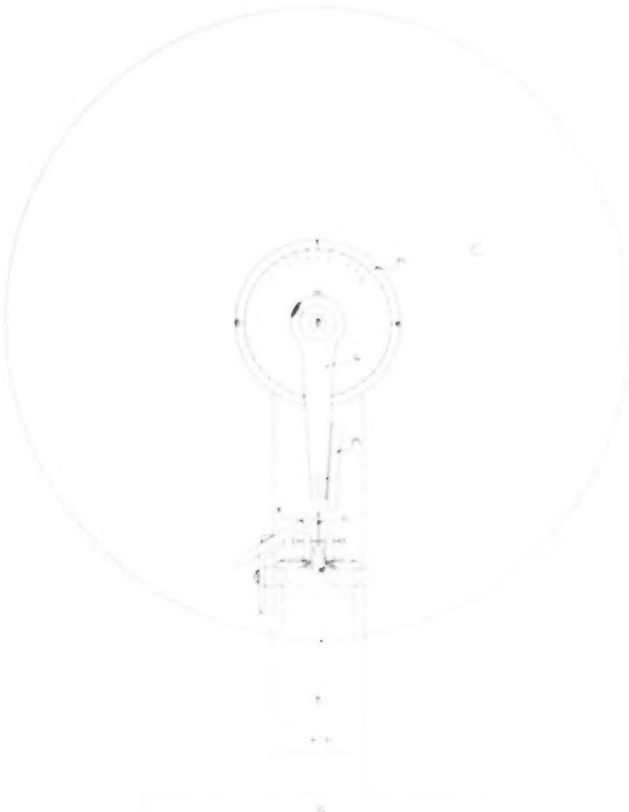


Fig. 2.

contacts on the automatic relay the make-current may be used, but is not so satisfactory on account of the variability. Since the current has the full time of the rotation of the shaft to establish itself, the break effect is almost absolutely uniform. Theoretically, there should be a slight difference in the loudness of the sound, depending on the rate of the interruption of the primary circuit; practically, no such difference is observable.

Another piece of apparatus which is used as an auxiliary to the complication instrument just described is a revolving shutter, composed of two sectored discs revolving in opposite directions on the same axis and in closely approximated planes. This shutter is placed in front of the eyes of the observer in such a way that the lines of vision of the two eyes are simultaneously cut off and then transmitted twice in each rotation of the discs. A metal plate with two eye-holes protects the observer from possible contact with the revolving discs.

On looking at the complication dial through the shutter revolving at high speed, the hand is not seen in motion but is seen in a series of different positions. By using an intense nitrogen lamp to illuminate the dial, the apparent brightness, which is reduced by the shutter, is brought up to normal. It would be possible to dispense with the shutter in front of the eyes and illuminate the dial by a beam of light interrupted by an episkotister, which would give somewhat the same effect, but for many purposes the revolving shutter is more satisfactory.

When using the revolving shutter, the observer is not only not tempted to make an eye reaction in the form of the following movement of the index hand, but finds judgment more difficult with such a movement. Hence, the avoidance of following movements is made very simple. This method does not, however, cut out all possible eye reactions.

DISCUSSION

In my article, The Influence of Inner Speech, etc., in the October 1916 number of this JOURNAL p. 365 ff., a few misprints occur. In the last line of Plate 7, the ditto marks under secs. and the words "R and" should be omitted. In Plate 8, " = 5 " in the first line, and the ditto marks under mins. in the last two lines should be omitted.

H. B. REED